Report no. 2023-R-13-EN

The role of e-scooters in the mobility mix

Opportunities and threats

FEDERALE OVERHEIDSDIENST
MOBILITEIT EN VERVOER

The role of e-scooters in the mobility mix

Opportunities and threats

Report no. 2023-R-13-EN

Authors: Vandael Schreurs K., Ben Messaoud Y., Dons E., Wrzesinska D., Deleuze J.

Responsible publisher: Karin Genoe

Publisher: Vias institute

Date of publication: 21/04/2023

Legal deposit: D/2023/0779/29

Please refer to this document as follows: Vandael Schreurs et al. (2023). The role of e-scooters in the mobility mix – Opportunities and threats, Brussels, Belgium: Vias institute

Ce rapport est également disponible en français.

Dit rapport is eveneens beschikbaar in het Nederlands.

Acknowledgements

The authors of this report and Vias institute would like to thank the Federal Public Service Mobility and Transport for funding this study.

Also, the authors thank the different municipalities in Brussels, as well as the police, that gave their consent for collecting data on their territory in relation to the behavioural and conflict observation part of this study.

Furthermore, thanks to the different shared micromobility providers and private stores that were willing to take part in interviews and share their knowledge to fill in the gaps of literature.

Lastly the authors would like to thank Philip Temmerman, who assisted on the practical assistance for the behavioural and conflict observation study part, and Tim De Ceunynck who externally reviewed this report.

Table of contents

VIAS institute

List of tables and figures

Glossary

[ACEM] European Association of Motorcycle Manufacturers	Represents the largest manufacturers of mopeds, motorcycles, tricycles and quadricycles with operations in Europe and can be seen as the motorcycle industry in Europe.
[BCW] Behaviour Change Wheel	Theory that takes constructs into account that are lying inside and outside of the individual, in order to explain why a certain behaviour is performed or not, and which interventions can facilitate or mitigate the behaviour.
[EPAC] Electrically Assisted Pedal Cycle	Electrically pedal assisted cycle with maximum speed of 25 km/h and maximal power output of 250W, excluded from Regulation 168/2013
[ISO] International Organization for Standardization	A worldwide federation of national standards bodies
[PET] Post-Encroachment Time	The time between the moment the first road user leaves the path of the second and the moment the second reaches the path of the first.
[PLEV] Personal Light Electric Vehicle	Light electric vehicles, covered by the CEN standard EN17128, that do not fall under Type Approval Regulation (EU) 168/2013, which are neither bicycles nor EPACs.
[PMD] Personal Mobility Device	Wide range of mobility products, including PLEVs, EPACs, and Type Approved powered cycles. This term is used in the context of the policy definition process started by the European Commission in 2019
[PTWs] Powered Two Wheelers	Part of the Light Category Vehicles (Type approval regulation 168/2013 L-Category), with two wheels in line, minimal bodywork and high power to weight ratio including categories L1e, L3e, and L4e.
[TTC] Time to collision	The time remaining until a crash between the vehicles would occur if they continued on their present course at their present rates.
BEV / EV	Battery electric vehicle / Electric vehicle
Environmental Impact Assessment	A methodology for assessing environmental impacts associated with a product.
ERG theory	Theory that tackles choices in terms of people trying to fulfil their needs (Existence, Relatedness and Growth)
First or Last-mile trip	Generally the first or last part of a mobility trip, that complements the main transport mode. This does not necessarily have to be a mile or kilometre. (e.g. a trip from the station to the workplace bicycle, when the train was taken as a main mode of transport)
ICE	Internal combustion engine
Interaction	A situation in which two road users arrive at a location with such closeness in time and space that the presence of one road user can have an influence on the behaviour of the other
L1eA	Powered Cycle category of the Light Category Vehicle Legislation (L-category)
L1eB	Moped category of the Light Category Vehicle Legislation (L-category)
Life Cycle Assessment / Life Cycle Inventory	A methodology for assessing all the stages of the life cycle of a commercial product.
Life cycle carbon footprint	Total carbon emissions considered over the total lifespan of a product

Micromobility device	Generic term encompassing any product intended for the transport of people or goods, self-propelled or not, that does not currently fall under Type Approval Regulation (EU) 168/2013 or is neither a bicycle nor an EPAC and has a relatively small size.
MONITOR	A comprehensive study of mobility and road safety patterns in Belgium, based on data from 30.000 adults and children.
Multilateral crash	Crash that happened between two or more road users
Near-crash	Potential crash that could be last-minute avoided.
Powered cycles (L1eA)	Electrically pedal assisted cycle with maximum speed of 25 km/h and power output between 250W-1000W, in the need of Type-approval according EU-regulation 168/2013
Safety Performance Indicator	Indicator that helps to determine whether or not an interaction can be considered as unsafe (e.g. TTC, PET, etc.)
Speed EPAC (L1eB)	Also called Speed Pedelec, which is an electrically pedal assisted cycle with maximum speed of 45 km/h and maximal power output of 4kW, in the need of Type-approval according EU-regulation 168/2013
Surrogate safety indicator	Indicator meant to be an alternative for safety analyses based on accident data (e.g. TTC, PET, etc.)
Tank-to-Wheel	Takes into account all resources/emissions/energy that are used from the energy storage location in the product to actual use (e.g. battery, gas tank, etc.).
Type approval regulation 168/2013	Regulation on the approval and market surveillance of two- or three-wheel vehicles and quadricycles
Unilateral crash	That happened with only one road user (e.g. ride against a static object)
Well-to-Tank	Takes into account all resources/emissions/energy that are used from extracting up to the energy storage location in the product (e.g. battery, gas tank, etc.).
Well-to-Wheel	Takes into account all resources/emissions/energy that are used from extracting to actual use.

Summary

An increasing urbanisation poses major challenges, of which traffic congestion is one. Next to the well known alternatives for private motorized transportation such as public transport, walking and cycling, or car sharing, personal mobility devices (PMDs) pose to offer a new solution. While originally designed for people experiencing difficulties with physical mobility, PMDs have known further developments turning them into a fully-fledged transport mode, resulting in a market boom. However, categorisation and legislation on these PMDs is often unclear. Even though a large focus is laid on mobility benefits, drawbacks are also present. Mobility insights are quickly outdated, the environmental impact gets questioned, and traffic safety is becoming a concern given the rise in injury crashes. This study was set up to gradually fill in the gaps that exist, focussing on mobility, the environmental performance, riding behaviour and conflicts, and self-reported (near) crashes. To succeed, a specific focus was laid on e-scooters, conventional bicycles and e-bikes.

Previous studies found that e-scooters replace walking, cycling, and public transport use. This study showed that e-scooters mainly impact car trips, have a slight positive impact on public transport use, and do not impact walking and cycling. Only e-bikes were found to impact public transport trips. While cars and public transport are used for all trip distances, their popularity is highest with longer trips. Bicycles are most popular for distances up to 2-5km, while e-scooters and e-bikes are most popular for distances up to 5-10km. Conventional bicycles, but also e-scooters are not solely seen as 'last-mile' options but as independent and fully fledged transport modes. With regards to ownership of PMDs, private e-scooters are most popular, however, shared use is also quite common. This differs for conventional bicycles and e-bikes that are more often privately-owned. In terms of the users, e-scooters are mainly used by young, employed men.. While youngsters find their way towards e-bikes as well, e-bike users tend to generally be somewhat older. Conventional bicycle users show a more even spread. To add, it was found that e-scooters are quite popular among people with a physical disability. However, further research is advised on this.

Transport mode choice was found to be heavily impacted by deeper underlying psychological constructs. This was proven by the psychological models, and the simple fact that having access to a mode doesn't make someone a regular user. In addition, a person who is using an e-scooter, isn't necessarily going to choose a bicycle if the e-scooter would be taken away. Higher order beliefs (e.g. contribution to society, positive impact on the environment, good feelings, health, etc.) were found to play a major role, even more important than utilitarian aspects (e.g. to meet friends, to go to the store, to go to work, to make multimodal journeys, etc.). For e-scooters, a higher interest in the social norm was also seen (e.g. use it because it is trendy, to show social prestige, to impress others, etc.). Next to that, factors could be identified that hinder the use of these transport modes. It was proven that motivational factors were most important (e.g. negative feelings towards safety, not making plans to use the mode, automatically thinking of the car, etc.). Subsequently, physical opportunity was important as well (e.g. a lack of time and money, not having the transport mode available, no well-maintained devices available, etc.). This could also be proven, since many non-regular users have no access to a bicycle, e-bike or e-scooter, or have a lack of available space to safely store them. Physical and psychological capabilities of a person had an impact as well (e.g. not enough strength, not enough physique, not enough skills, not enough focus, etc.). Social support of others was less important. In fact, the role of physical activity cannot be ignored, since regular users were more physically active compared to their non-regular user equivalents, which also had a positive effect on the physical limitations that were a hindering factor for the use of the transport mode.

Next to mobility concerns, suspicion around the environmental performance of e-scooters was also raised. Although e-scooters have no direct tailpipe emissions, concerns were raised in earlier performed studies due to the short lifetime and highly polluting battery production process. This lead to emissions of 110-165 g CO_2 eq/vkm, on par with a typical internal combustion engine car. The presumed short lifetime and the use of polluting fossil fuel service vans to transport and charge shared e-scooters caused this bad figure. By contrast, our study (based on updated numbers) found CO_2 emissions of 36g/vkm for a recent private e-scooter and 49g/km for the newest generation shared e-scooter. This is better than other motorized transport modes (e.g. ICE car, EV car, and bus) for which it can be seen as an alternative. This improvement can be explained by the increased lifetime of e-scooters, better maintenance, and more efficient operations. In fact, the largest portion of these emissions are caused by the vehicle production process (i.e. 50-80% of the total life cycle emissions), and operational services for the shared equivalents, while initial transport to Belgium, the efficient drivetrains of e-scooters, and the sustainable electricity mix in Belgium (in terms of CO_2) has a negligible contribution.

However, life cycle GHG emissions (Greenhouse Gas Emissions) of an e-scooter are very sensitive to changes in the lifetime mileage and life years. An e-scooter that lasts only half as long and is ridden only half as much, has life cycle GHG emissions almost four times the initial number, quickly becoming more polluting than fossil fuel cars. Furthermore, lower servicing distances can also aid a lower output of GHG-emissions, for example by shifting from free-floating devices to docking-station based supply. While this is true for shared devices, the largest environmental benefits for private e-scooters are in the vehicle production phase, where large quality differences on the market can have a big impact on the vehicle's lifetime and its life cycle emissions.

While the lifetime of the e-scooters is a crucial parameter, estimating it is difficult due to many innovations and quick renewal of models, and confidentiality of lifetime data on the side of the shared e-scooter providers. This study highlights the need for regulation and transparent communication about the performance of micromobility devices.

Road safety deemed to be another issue of concern. Previous research found that pedestrians and cyclists feel safest when e-scooter users ride at a maximum speed of only 15 km/h, or if they get overtaken at a maximum speed of 10 km/h. However, this is considered slow by e-scooter users and is lower than their average ridden speeds. This could be seen in this research by the high share of speeding infractions (i.e. 30% to 60%) by e-scooter users in pedestrian zones, where a speed limit of 8km/h was set. In general, speeding and non-adapted speeds were found in both e-scooter users and cyclists, but they were higher in e-scooter users. To add, in 1 out of 4 conflicts observed, the speed limit was not respected (both for cyclists and e-scooter users). Furthermore, this research found that e-scooter riders have a higher risk for a conflict compared to bicycle users considered over the number of users, but not over the number of interactions. Furthermore, riding with a passenger on the e-scooter was found to occur in 10% of the users, but did not seem a major cause in conflict occurrence.

In relation to crashes, underreporting is a big problem. Only a fraction of the crashes by (e-)bike or e-scooter is registered by the police: it was found that only 10% of the self-reported crashes resulted in a more severe injury for which a doctor visit was needed. In fact, the injury severity mainly increases when another road user was involved in the crash. No difference in the risk of rider fatality per trip between e-scooters and bicycles is found in literature, but the risk for hospitalisation appears significantly higher with e-scooter riders compared to cyclists. While the crash severity was not very serious based on the self-reported crashes in this research, it has to be kept in mind that e-scooters are mainly used by younger and less vulnerable users, compared to – for example - older users with e-bikes. On the other hand, it was found that e-scooter users less frequently possess any kind of driving license. It is plausible that a lack of adequate knowledge is present (i.e. knowledge that is often obtained for a theoretical exam to achieve a driving license), which can be for a factor in the higher ratio of crashes per vehicle kilometer travelled.

Self-reported crash data showed that e-scooter crashes are largely unilateral (i.e. 4 crashes out of 5), which is the opposite of PV analyses. Their causes are related to technical problems, own behaviour, and weather conditions for e-scooters, while cyclists mainly report road infrastructural problems and their own behaviour as crash causations. In multilateral crashes the behaviour of the other road users is often indicated as a crash cause, but own behaviour is also mentioned by e-scooter users. The high share of technical issues, as a crash causation for e-scooters, can not be explained. Further research on this aspect is advised. Based on literature, a high presence of head injuries is present in e-scooter crashes

From all of these insights, specific recommendations in the field of PMDs were made. These recommendations focus on the legal and technical framework for PMDs, travel behaviour and mode choice, environmental impact, and safety and can be found at the very end of this report.

While this study was able to provide new insights in the topic, some limitations were present as well. Given the breadth of this study, it was not possible to foster a deeper exploration of certain aspects or interesting findings. Next, the methodology to research mobility differed from previous work performed on the topic making direct comparisons not possible. Furthermore, a questionnaire was used to gather mobility and crash information which potentially induced a social desirability or a recall bias. Lastly, assumptions had to be made in the life cycle assessment, including information from shared providers that might have led to an overly optimistic environmental performance.

While these study limitations cannot be ignored, it can be concluded that PMDs (and more specifically e-scooters) have a positive effect on mobility in general and the environment. Caution is needed when it concerns traffic safety, given the higher crash and conflict risks compared to bicycles and the associated higher injury levels. Traffic safety is important to address in order to reap the benefits of this specific transport mode. In a world in which a shift to more sustainable transport modes is absolutely necessary, these devices can contribute to a better environment. Furthermore the results of the study show that higher order beliefs are becoming more important in transport mode choice than mere derived demand and the need to move from A to B. E-scooters, e- bikes, and conventional bicycles have their own specific field of use and are not just replacing one another. While it is possible that e-scooters, e-bikes, and bicycles can be rivals of each other for specific trips (e.g. an e-scooter is equally often used as a bicycle for first-last mile trips), the collective effect on the replacement of car trips, seems to be a more beneficial effect. In fact, more focus should be laid on the potential of e-scooters to contribute to better living environments.

1 Introduction

With an increasing urbanisation, ever-increasing traffic congestion is undeniable. Next to the well known alternatives such as public transport, cycling or even car sharing, personal mobility devices (PMDs) pose to offer a different solution. Moreover they are affordable, accessible and easy-to-use. Yet some of these devices tend to have a bad reputation, especially with respect to health, traffic safety, and environmental sustainability. A lack of knowledge on these devices, due to the fast development, hinders the government from taking effective actions. This study was set up to gradually fill in the gaps that exist in relation to their role in daily mobility, environmental performance, riding behaviour, safety, and influence on transport mode choice (e.g. cycling, walking, public transport use).

The report is drafted in such a way that the individual chapters can be read separately. However, to get a full overview, it is recommended to read the full report.

In chapter 2 of this report, focus is laid on mobility information, that was collected through questionnaire research on regular and non-regular users (or non-users) of e-scooters, bicycles, and e-bikes, by means of a national representative sample in Belgium of 1.088 respondents. This chapter aims to provide more insights in the mobility aspects that are still underexplored to date.

In chapter 3, the environmental impact of e-scooters is addressed. This was explored by means of a Life Cycle Assessment and Environmental Impact Assessment, based on recent literature.

Next, chapter 4 and 5 report on traffic safety. In chapter 4, behaviours of e-scooter users and cyclist are studied by means of a behavioural observation and conflict observation study in shared spaces with pedestrians, cyclists and e-scooter users in Brussels. Subsequently, chapter 5 discusses the aspect of (self-reported) crashes and near crashes, together with recent findings from literature.

Finally, chapter 6 and 7 respectively discuss the results and provide recommendations.

To start, a brief background is provided in terms of the different mobility devices that were taken into account for this research, as well as the topics assessed in this report, namely: trip characteristics and daily mobility, environmental impact, behaviour, and crashes.

1.1 Categorisation

The categorisation and terms that appear in the field of personal mobility devices (PMDs) are diverse and can lead to confusion. In order to clarify the different categories and scope of this research, some definitions are provided. ACEM (the motorcycle industry in Europe) made an overview of personal mobility devices. While the use of these terms is not universal throughout literature, this categorisation created by the motorcycle industry is not illogical, since most of these personal mobility devices are motorised and therefore categorizable in the field of Powered Two Wheelers (PTWs). ACEM (2021) provides the following definitions:

- PMD (Personal Mobility Device): "covers the widest range of products, including EPACs (Electrically Assisted Pedal Cycles) and Type Approved powered cycles classified as L1eA. This term is used in the context of the policy definition process started by the European Commission in 2019."
- Micromobility devices: "Generic term encompassing any product intended for the transport of people or goods, self-propelled or not, that does not currently fall under Type Approval Regulation (EU) 168/2013 or is neither a bicycle nor an EPAC."
- PLEV (Personal Light Electric Vehicle): "light electric vehicles, covered by the CEN standard EN17128, that do not fall under Type Approval Regulation (EU) 168/2013, which are neither bicycles nor EPACs."

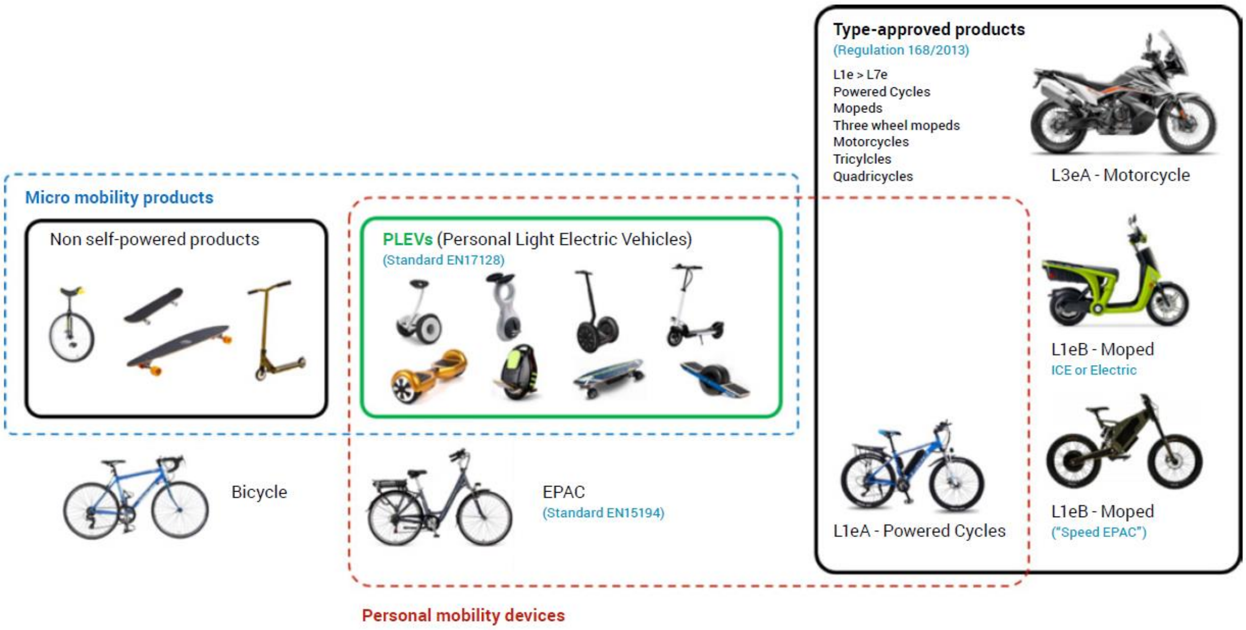


Figure 1: Overview of personal mobility devices with exemption of utility vehicles (ACEM, 2021)

Initially, this research aimed to focus on Personal Mobility Devices (PMDs) and conventional bicycles (note that conventional bicycles do not fall under the scope of PMDs based on the previous definitions). However, in order to succeed, the broad spectrum of PMDs had to be narrowed down. This lead to the **selection of e-scooters** (electric kick scooters), **e-bikes** (EPAC and Powered Cycles Category L1eA), **and conventional bicycles for this research**. To ease data collection, speed pedelecs (i.e. speed EPAC category L1eB) were also taken into account in the category of e-bikes, even though they are not part of the PMD category.

This specific selection was made, because PMDs are a relatively new type of vehicle, resulting in a limited number of scientific studies. Out of these studies, most focus on e-scooters, and particularly shared e-scooters (European Commission, 2021). E-scooters are currently one of the most popular and widely used micromobility devices, which increases the relevance of this study, and also the likelihood of recruiting a sufficiently large sample of regular users for this research.

1.2 Mobility

PMDs were originally designed for people experiencing difficulties with physical mobility. However, new technological developments and chronic congestion of urban transport networks, have led to a further development and creation of new PMDs (European Commission, 2021).

Figure 2: Early PMD device

Now, PMDs know a market boom (visible in the European Shared Mobility Index[1]) and aim to be an easy way to travel around the city, to promote sustainable modes of transportation over short distances by proposing alternatives to private cars, and try to contribute to solving the "last-mile" problem (Brannigan et al., 2022; European Commission, 2021; Vias institute, 2021). The last mile problem describes the difficulties people experience while travelling the first or last mile between their starting point or final destination and a public transportation hub. The use of privately owned or shared e-scooters can be seen as a means of doing so. However, it is believed that shared e-scooters are mainly used for leisure activities, during the weekend and by young men, while privately owned e-scooters are more often used for commuting (European Commission, 2021).

[1] The European Shared Mobility Index provides quarterly snapshot of the market across 20 cities, selected to highlight diversity in size, geography and market characteristics. The Index encompasses shared bikes, scooters, mopeds and cars (Polis, 2022)

PMDs have the potential to contribute to local sustainability objectives by means of reducing car dependency (addressing traffic congestion, noise, delays, stress), increased accessibility/mobility in urban areas, replacing private car trips, and thus inducing a modal shift (Brannigan et al., 2022). E-scooters specifically, are believed to replace up to half of the car trips in cities, leading to the expectation that they will become an important transport mode in urban areas (Vias institute, 2021). However, findings between studies differ largely in the degree to which e-scooters in fact replace car trips (De Ceunynck et al., 2021).

Other benefits often mentioned are (Brannigan et al., 2022; Vias institute, 2021):

- Their affordability and cost-effectiveness
- Increased accessibility in urban areas
- Reduced physical effort compared to bicycles (which in its turn leads to less sweating and easier use of office clothing)
- More environmentally friendly compared with motor vehicles (discussed more in detail in section 1.3)
- Convenience and flexibility
- Compatibility with other modes of transport (e.g. public transport)

However, potential challenges are mentioned as well. Critics argue that e-scooters will make people walk less (European Commission, 2021), and that a modal shift could occur from bikes and public transport to e-scooters which reduces physical activity and the associated health benefits (Brannigan et al., 2022).

While more and more insights in mobility are provided for these PMDs, still a lot of work on mobility has to be performed. While on one hand, some mobility insights are quickly outdated due to the constant change in use, growth of the sector, and societal changes (e.g. COVID-19 pandemic). On the other hand the direct link between the use of PMD modes and conventional bicycles is seldomly made in the same study. While figures are often compared between studies (each with their own limitations), trying to estimate the modal shift, a direct comparison between regular users and non-regular users of these different transport modes is seldomly performed. With this in mind, the mobility characteristics of e-scooters, bicycles and e-bikes are explored in this study.

1.3 Environmental impact

Focussing on micromobility devices, and specifically e-scooters, their environmental impact is often questioned. Recently, concerns about the life cycle carbon footprint have been raised, which has also been challenged for EVs. To add, large differences are present in recent literature in relation to CO_2 emissions emitted (largely indirectly) by e-scooters. To illustrate differences ranging from 36g and 60g CO_2/km to 165g CO_2/km can be observed, for which the latter is similar to a passenger car (de Bortoli, 2021; Hollingsworth et al., 2019; Kazmaier et al., 2020; Licata, 2021; Moreau et al., 2020; Severengiz et al., 2020).

Claimed benefits of e-scooters include the potential to reduce traffic congestion and greenhouse gas emissions (Brannigan et al., 2022), when compared to other modes of transport. But without a proper framework, these claims are hard to assess. For example, since e-scooters do not have tailpipes, they do not emit any greenhouse gases directly. However, they do have a significant secondary carbon footprint due to other phases of their life cycle such as manufacturing, charging, and maintenance processes. To properly identify the impact on the environment of the different stages of the life cycle of an e-scooter, a life cycle assessment should be performed.

While privately owned e-scooters can be used whenever the user likes to, shared e-scooters are made available to the public by service providers for a fee, consisting of an activation fee supplemented with a fixed rate per minute of usage. After arriving at the destination, the user leaves the shared e-scooter on the public domain, preferably without hindering other road users (free floating), or at designated parking spots, depending on the local regulations and company policies. As a result, mainly the company providing the service takes care of the charging and maintenance of the e-scooters and has to take into account the environmental impact of its service.

As the market grows, a rigorous evaluation of the potential environmental benefits and risks becomes more and more important. Experts estimate that the global shared e-scooter market will experience a boom up from 774.000 units in 2019 to more than 4 million shared e-scooters in operation worldwide in 2024 (The Brussels Times, 2020).

Since the market on e-scooters is developing quickly (both privately owned and shared use), environmental effects often have to be revised. Large differences between generations of e-scooters exist (e.g. the lifetime of the e-scooter, the servicing and recycling strategies, etc.), which can potentially lead to an outdated evaluation of their environmental performance. It is therefore essential to get insights into the environmental performance of the current generation of e-scooters, for example by means of an environmental impact assessment. Contrary to what one might think, it is not clear if a legally binding framework exists for such an assessment.

1.4 Riding behaviour

PMDs share the same space as pedestrians[2], cyclists, and/or motorised traffic, depending on the location. Not only do they have a higher mass than pedestrians, they also travel with higher speeds (so do cyclists), which can lead to conflicts. To add, PMDs are also quiet and equipped with less visible lighting, making them difficult for other road users to anticipate on (European Commission, 2021). This seems to be especially true in shared spaces, such as pedestrian zones, where these different road users are mixed, potentially causing safety problems (Martensen et al., 2021). On top of that, more and more cities receive complains about unsafe situations in these shared spaces due to the presence of PMD users (especially e-scooters) (European Transport Safety Council, 2022).

The riding behaviour of PMD (and especially e-scooter) users is crucial for road safety. Service providers should take their responsibility to provide a safe service for all (European Transport Safety Council, 2022). Irresponsible behaviours such as speeding, driving on footpaths, random parking, vandalism, etc. are negatives that often appear in the media (Vias institute, 2021). As a result, policy makers are concerned about the behaviour of e-scooter users. While more studies are being performed nowadays, insights in real behaviours are still limited. Most information retrieved focusses on hospital studies and some (limited) observational studies (Vias institute, 2021). This often leads to a specific focus on drink-driving, helmet wearing, maximum speed, the place on the roadway, and parking (European Commission, 2021). Unfortunately, conflicts are not often researched.

Nonetheless, a better understanding of behaviours and conflicts is necessary on e-scooter users and cyclists in shared spaces. Because of this, a behavioural and conflict observation study is performed in this research to get more insights in the underexplored aspect of e-scooter safety, including the differences between bicycles and e-bikes in these same situations.

1.5 Crashes

Although certain benefits of e-scooters, e-bikes and bicycles are undeniable, questions arise about the risks of PMDs. While they were introduced to reduce motorised traffic, an increase in the number of injuries can be observed (European Commission, 2021).

In 2021, 34,640 injury accidents were officially registered with a vast range of transport modes on the Belgian road network. Compared to the number of injury accidents that occurred in 2019 on the Belgian road network (i.e. 37,719 injury accidents), an 8% decrease could be noted in 2021. During that same time period however, 1,034 injury accidents with e-scooters were recorded in 2021, which is an increase of 153% compared to 2020 (a non-reference year due to COVID-19) and even an increase of 491% compared to 2019. This means that a high increase in e-scooter injury accidents is present, parallel with a decrease of the total number of injury accidents with other transport modes. Indeed, the substantial increase in exposure can explain a large part of this rise, as a year on year trip growth of 124% could be observed in 2021 compared to 2020 (Fluctuo, 2022). In any case, these crash statistics raise concerns with policy makers and traffic safety experts. Especially since e-scooter crashes are paired with a lack of crash statistics and insights (although crash registration has improved lately). While information on crashes with bicycles and e-bikes is quite readily available, information on e-scooter crashes is still scarce. Only recently a first crash causation study[3] was performed in Belgium by De Vos & Slootmans (2023), which gives insights in injury crashes with e-scooters, for which police presence was necessary.

[2] As from July 1st 2022, PMDs are not allowed to use the footpath anymore in Belgium (except for those users that experience reduced mobility). However, do they still share the same space in shopping streets, pedestrian areas, shared spaces, etc.

[3] The crash causation study by De Vos & Slootmans (2023), performed in parallel with this study, can serve as a good addition to this report. Furthermore it can serve as a comparison with the observational and self-reported crash information of this study.

To add, crashes only portray a small picture of issues related to traffic safety, due to their rarity (De Ceunynck, 2017). It is assumed that they do not reflect the total reality due to underreporting of crashes, which is thought to be largely present within e-scooter crashes. As a solution, hospital data are often used. While providing, on some occasions, more information than official crash statistics, the issue of underreporting is still present since, luckily, not every crash results in a hospital visit. Due to this, an approach focussed on near-crashes or self-reported crashes can be used. While near-crash studies use well-thought-out methodologies, the gathering of self-reported crashes is quite a simple and straightforward process. Self-reporting of crashes is a useful tool that can be used as a complementary method to obtain more information on crash events, and to close the gap due to underreporting of crashes. However, it remains important to acknowledge that the largest issue with self-reporting concerns the possibility of socially desirable answering and forgetting about minor crashes that happened longer ago (Kamaluddin et al., 2018).

Since a questionnaire was foreseen in this study to collect mobility information, the opportunity was taken to add the element of self-reported crashes and near-crashes. Together, with the near-crash section of this study by means of conflict observation, and the insights on crashes through (De Vos & Slootmans, 2023), this serves as an addition to gain a better overview on e-scooter crashes and severe conflicts.

2 PMDs and their mobility

2.1 Methodology

In order to get more insights into regular ruse and non- regular use of e-scooters, e-bikes, and conventional bicycles, a questionnaire study was performed.

Target groups were created based on three transport modes of interest (i.e. e-scooters, bicycles, and electric bicycles including speed pedelecs). For each of the target groups, 2 subgroups were defined, namely regular users and non-regular users of the transport modes of interest. This way, six respondent groups were formed in total: regular users of e-scooters, non-regular users of e-scooters, regular users of e-bikes, non-regular users of e-bikes, regular users of conventional bicycles, non-regular users of conventional bicycles.

In order to categorise regular users and non-regular users, a distinction was made based on the frequency of use. The questionnaire started with a selection questionnaire, consisting out of a demographic information section and a categorisation section to classify the respondent in one of the six categories (as shown in table 1). People that would use one of these modes on a daily or weekly basis were seen as regular users, while non-regular users are considered to be people that use the transport mode less often than on a weekly basis or not at all.

Table 1: Selection question

	I use it daily	I use it weekly	I use it multiple times a month	I use it ≤1 a month	I used it in the past but not anymore	I don't use it
 E-scooter	a)	b)	c)	d)	e)	f)
 E-bike	a)	b)	c)	d)	e)	f)
 Conventional bicycle	a)	b)	c)	d)	e)	f)

Based on the answers of the respondent in the selection questionnaire, the appropriate questionnaire was offered. If participants used multiple transport modes, priority was given to the questionnaire that tackled more difficult to reach users (e.g. if a person used an e-scooter and bicycle both on a weekly basis, the e-scooter questionnaire was provided over the bicycle questionnaire). For non-regular users the same approach was used in reverse manner, focussing principally on transport modes for which is believed that it is used the most (e.g. if a respondent indicates to use neither of the transport modes, priority is given to the bicycle questionnaire, since non-regular users of bicycles are more difficult to find that non-regular users of e-scooters or e-bikes).

The questionnaire was sent out to a nationally representative sample within a polling agency. On each of the respondent groups, targets were placed. For the non-regular users of each transport mode, a target of 250 respondents was set. For the regular users, 120 participants were envisaged (since user groups were more difficult to find). Identical questionnaires were created only differing in the transport mode questioned.

Sampling always continued nationally representative. The different groups were filled in automatically based on the answers of respondents. When one respondent category was full, the sampling continued nationally representative to keep filling in the other categories. This sampling continued until all defined categories reached the target size (i.e. 250 non-regular users and 120 regular users). Only for e-scooter users, a small boost had to be performed to reach the desired target size.

In total, the sample size consisted out of 1088 participants. However, to reach this sample size, much more respondents had to be sampled to remain compliant with the national representative sampling (e.g. if 500 respondents complied with the predefined targets, much more respondents filled in the selection questionnaire). For each transport mode of interest roughly 250 non-regular users (i.e. 22% of total sample for each mode) could be achieved. For e-bikes and conventional bicycles 120 regular users (11% of total sample for each mode) could be identified, while for e-scooters 90 regular users (8% of total sample) were recruited (due to data-cleaning a part of the respondents had to be filtered out).

To note, an overrepresentation of regular e-scooter users in the province of Hainaut was observed (possibly due to the boost on regular e-scooter users, or the recent rise of e-scooter leasing schemes, which were found to be very popular in Charleroi).

Figure 3 illustrates that a conventional bicycle is used most often, while e-scooters are used least often.

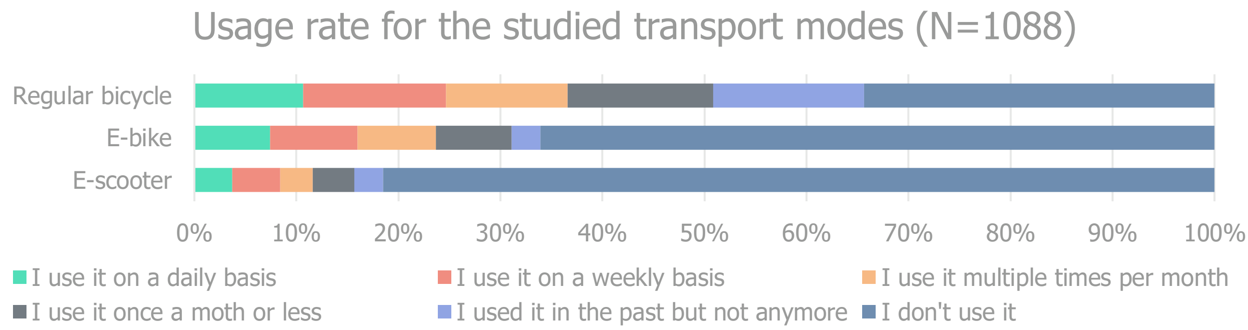


Figure 3: The usage rate of e-scooters, e-bikes and conventional bicycles

Questions focussed on demographic information, modal split information, availability of transport modes, accessibility of transport modes, distances travelled, and reasons for using (or not using) one of the selected transport modes.

2.2 Sample description

Results show a statistically significant difference based on gender, in which men are slightly more present than women in each of the regular user categories (i.e. around 2% more male users than female users). For non-regular users, the opposite is found.

Further, an average age of 48 years old could be observed within the total sample. Regular e-scooter users and regular users of conventional bicycles clearly show a lower average age (i.e. respectively 37 and 44 years old), while regular e-bike users show a higher average age (i.e. 52 years old). This age difference is also visible in figure 4, in relation to the different age categories. Regular e-scooter users are generally younger, while regular e-bike users tend to be older. For conventional bicycles, a more even spread seems to be present. Nevertheless, it has to be mentioned that youngsters more and more find their way towards e-bikes (De Maeseneer, 2018; Federale Overheidsdienst Mobiliteit en Vervoer, 2022), however, a share of 20.6% of e-bikes users younger than 36, in this study, is in fact in line with other data recently gathered on cycling in Belgium (Federale Overheidsdienst Mobiliteit en Vervoer, 2022).

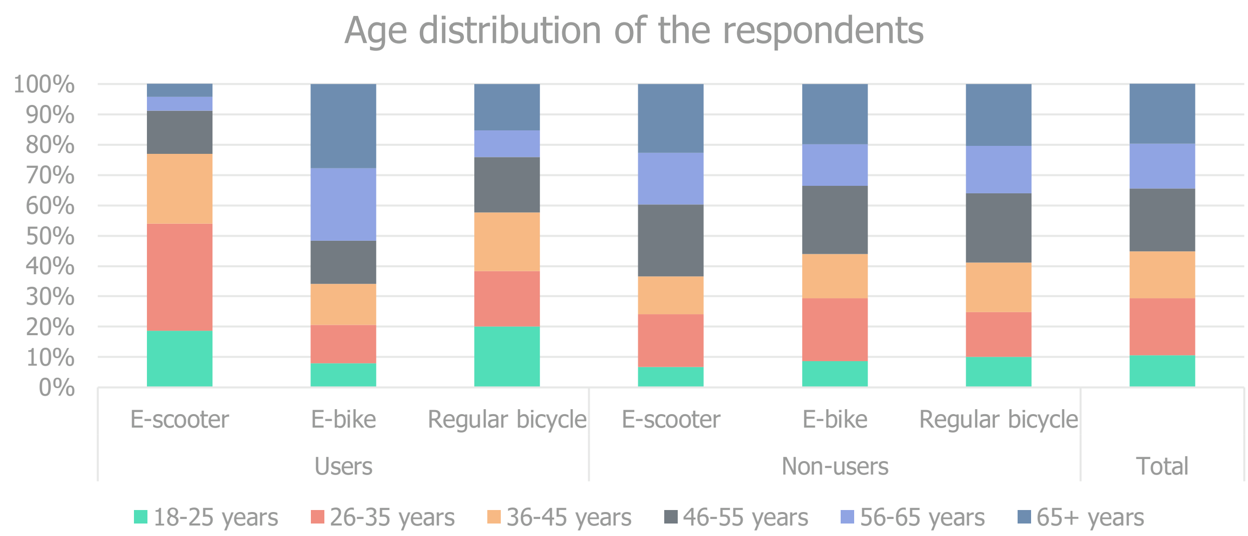


Figure 4: Age distribution of regular users and non-regular users of the different transport modes of interest

With regards to the main activity/occupation of the respondents, the biggest proportion are fulltime employees, followed by respondents that are retired. Other main activities/occupations are less often present (i.e. self-employed, students, housewives/househusbands, disabled, and jobless). Here some differences can be observed as well, which can further be related to the age differences found previously.

As visible in figure 5, regular users of conventional bicycles seem to have a larger proportion of students and employees, but less pensioners, which can explain the more even spread in age categories and mean age of the regular users of conventional bicycles. Their lower cost of ownership could explain the popularity with students (and partly for employees), while older persons can be put of by the higher physical effort needed to propel the bicycle compared to an e-bike. The latter can be an explanation for the drastically bigger proportion of pensioned regular users of e-bikes.

For e-scooters, the number of employees is drastically higher, while the number of pensioners is drastically lower. Students are also using this mode of transport a bit more often. The nature of the e-scooter (i.e. rather fast, unstable, etc.) probably makes it less popular for older persons while the flexibility of the mode makes it probably more popular for employees (e.g. last-mile) and students.

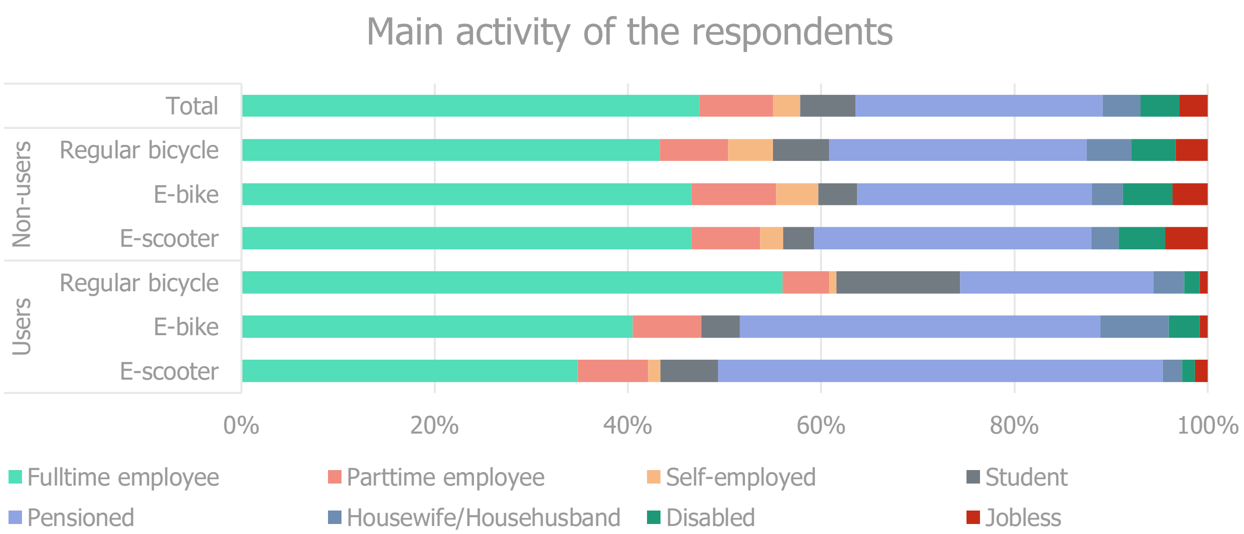


Figure 5: Main activity of the respondents

The level of education shows that the largest portion of the sample is holding a degree for Secondary education (50%), a Bachelor's degree (28%), or a Master's degree (17%). It also shows that regular users of e-scooters tend to be higher educated compared to regular users and non-regular users of the other modes. For the other modes less pronounced differences are present.

Different (net household) income levels could also be observed within the sample, with a large portion of respondents with a low to middle income (i.e. <4.500€ per month). Statically significant differences are present between regular users and non-regular users, but are rather small and ignorable. Regular e-scooter users tend to have a lower net income compared to other regular users of other modes (possibly impacted by a higher share of respondents preferring not to answer).

Taking the geographical spread into account, the results show that bicycle and e-bikes are more popular in Flanders, while e-scooters tend to have a more even spread with a slightly bigger share of regular users living in Brussels, Liège, and Hainaut. Within the non-regular users a more even spread is found, comparable to the shares of inhabitants in each province.

The domicile of these regular users is also well distributed in terms of the living environments (i.e. urban, suburban, periphery, and rural). It can be observed in figure 6 that regular users live more often in (or closer to) an urban environment compared to non-regular users. Especially with regular users of e-scooters, the proportion living in (or close to) an urban environment is the highest. E-bikes are also popular in the periphery.

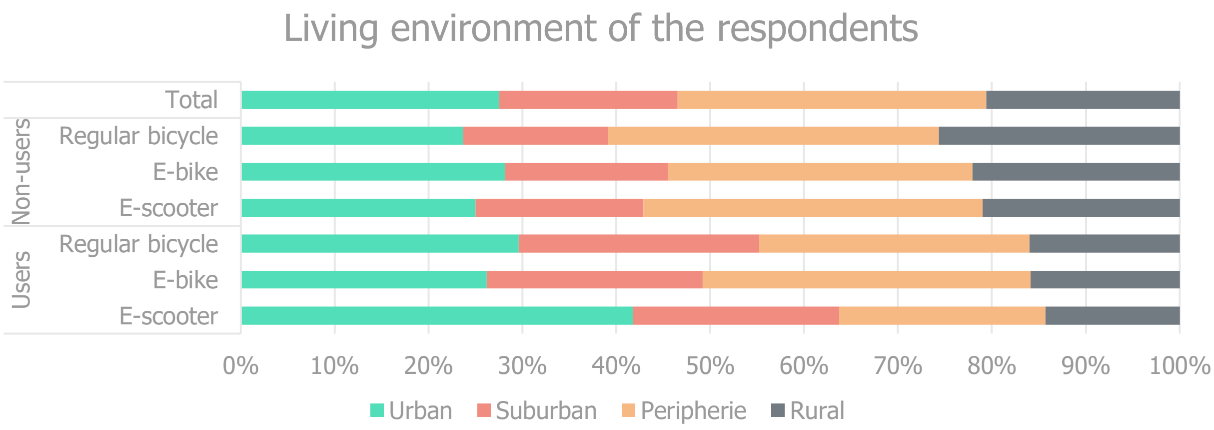


Figure 6: Living environment of the respondents

Subsequently, respondents were asked whether or not they suffer from any kind of permanent or long-term disability[4] (e.g. chronic fatigue syndrome, long term injury, missing or non-functional limb, etc.). In general 9.7% of the respondents completing the questionnaire indicated to have a disability. However, more interestingly, the data shows that people with a disability are less often present within regular users of conventional bicycles and e-bikes (i.e. respectively 3.2% and 5.6%), but vastly more present within regular e-scooter users (i.e. 30.8%). Based on this finding, it seems that an e-scooter potentially has benefits for people with a permanent or long-term disability. Due to the diversity of possible disabilities, it is important to conduct further research. Nevertheless, interviews with providers shed light on this aspect, in which was found that, for example, wheelchair users make use of shared e-scooters to propel their wheelchair for further distances.

The frequency of physical activity that induces physical fatigue (e.g. running, cycling, working in a labour intensive sector, etc.) was also questioned. Figure 7 shows that regular users of e-scooters, e-bikes and conventional bicycles are more physically active compared to non-regular users. Regular e-bike users are the most physically active, possibly due to the active nature of the transport mode.

[4] Based on the question: "Do you have a permanent or long-term limitation/disability that prevents you from using "normal" active means of transport? (e.g. Lost arm, long-term injury, chronically fatigued, which would prevent you from getting around using a normal e-scooter or bicycle)

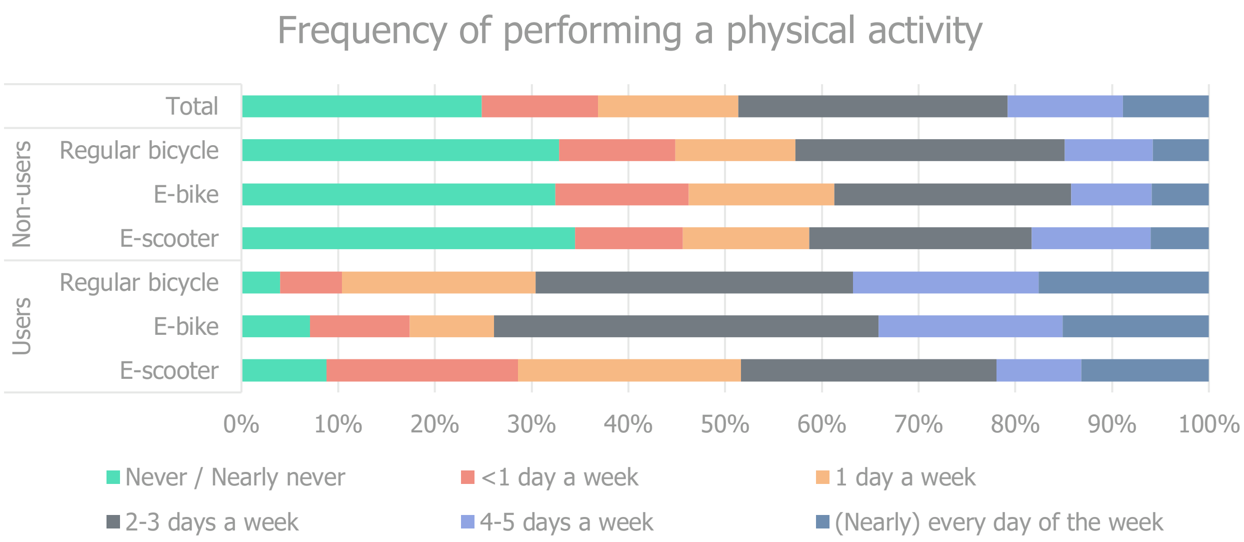


Figure 7: The frequency in which the participants perform any kind of physical activity

Lastly, as shown in figure 8, differences in driving license possession between regular users and non-regular users are mainly absent, except for regular e-scooter users. Regular e-scooter users possess less frequently any kind of driving license. 28% of the regular e-scooter users isn't holding any driving license. For the other regular users and non-regular users a range of 12% to 20% is visible.

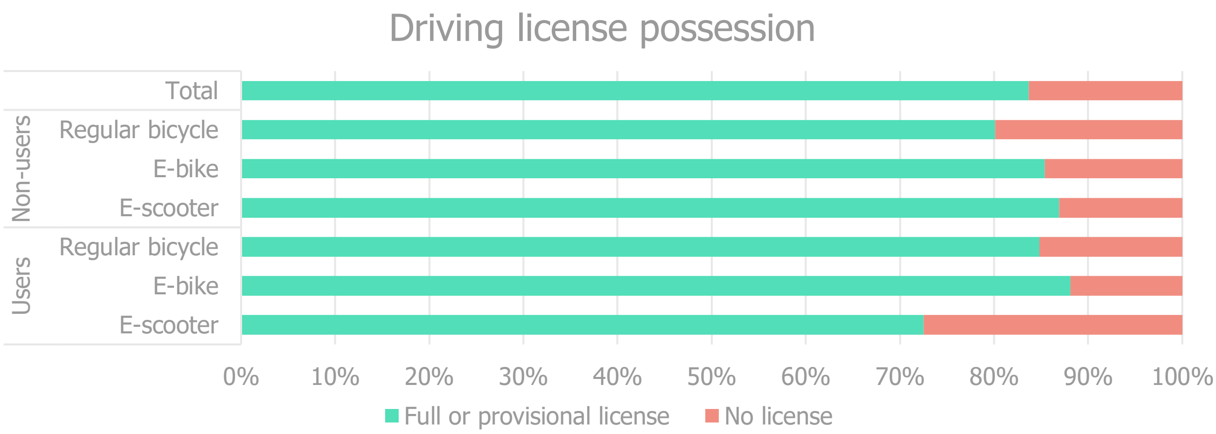


Figure 8: The share of regular users and non-regular users of the transport modes of interest that are holding any kind of driving license

2.3 Modal split

A further look was given to the modal information to get a more detailed insight on the transport modes that are being used.

First an overview is given in figure 9 on the ownership of transport modes. In the total sample, without making a distinction between regular users and non-regular users, it is clear that a car is possessed most frequently (i.e. one or two cars are most often present in the household, which is consistent with MONITOR data (FOD Mobiliteit en Vervoer, 2022)). Next to the presence of a car, a conventional bicycle is also very frequently owned. Owning multiple bicycles is not uncommon, even for people that can be considered as non-regular users. For e-bikes, the owning rate is much lower. This could be explained by the larger cost of an e-bike, since respondents with a lower income indicate more often not to possess an e-bike. Privately owning an e-scooter is quite marginal.

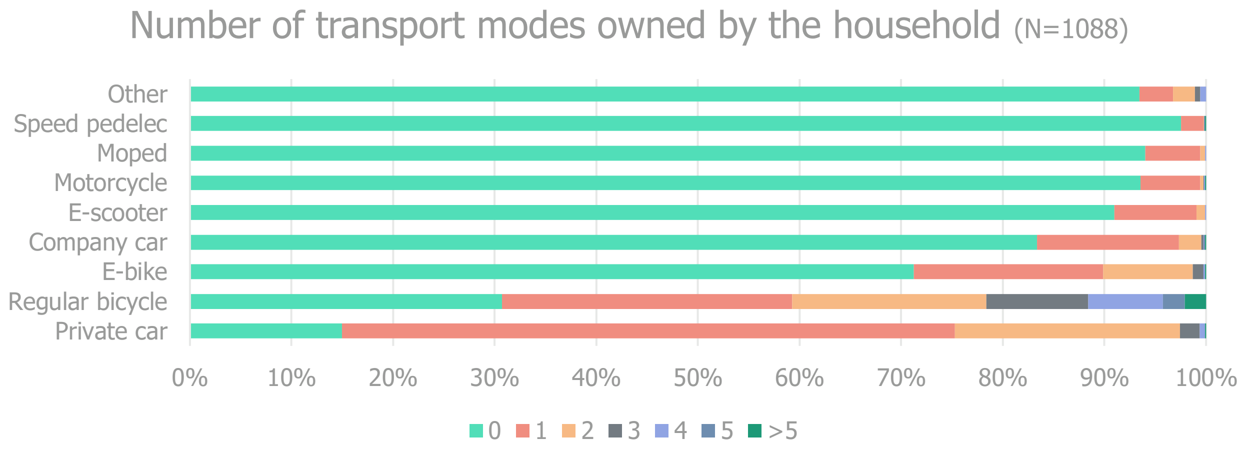


Figure 9: The number of transport modes that are owned in the household of the participants

Subsequently, a differentiation was made, focussing only on the regular users of e-scooters, e-bikes, and conventional bicycles, whether or not they use it via a shared provider or by privately owning it. Figure 10 shows that regular users of e-bikes and conventional bicycles mainly possess their bicycle privately. Shared use is very marginal (<3%) and is slightly higher for conventional bicycles.

Although the ownership of e-scooters was marginal in the total sample (all regular users and non-regular users), roughly 2 out of 3 regular e-scooter users makes use of a privately owned e-scooter. Shared e-scooters are used by 70% of the regular e-scooter users (i.e. 40% does indicate to use it and another 30% indicated to have used one in the past but not anymore, which could be an effect of the COVID-19 pandemic and increased telework). 30% of the regular e-scooter users is not using a shared scheme. However, it has to be mentioned that one person can both use a private device as well as a shared scheme.

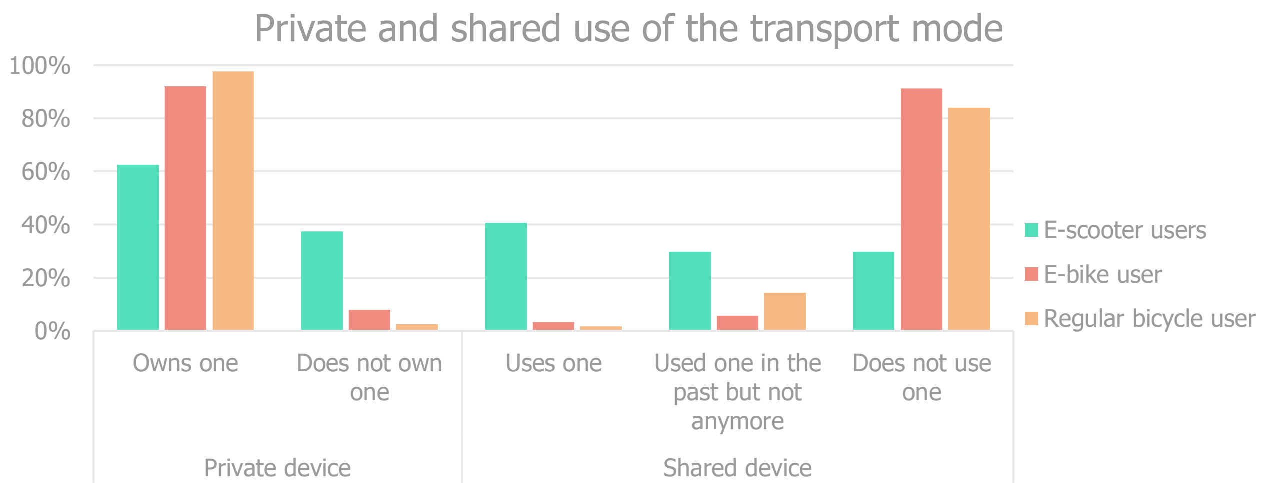


Figure 10: The shares of private and shared use of the transport modes of interest

In order to better understand this finding, a specific look was given in figure 11 to those regular users that indicated not to own a private device, and how this relates to the use of a shared device.

For conventional bicycles and e-bikes, the number of regular users not having a private device was already quite marginal (i.e. <8%). Out of these, some indicate to have used a shared bicycle in the past but not anymore, or specifically indicate not to use a shared bicycle.

Out of the regular e-scooter users, that do not own a private device, 85% uses a shared device (i.e. 41% is using a shared device and 44% used a shared device in the past but not anymore, which could partly be explained by a COVID effect due to telework). 15% of the regular e-scooter users, that are not owning a private e-scooter, are proclaiming not to use a shared e-scooter either. This can portray a completely separate way of using e-scooters, possibly explained by private sharing (e.g. cohousing where one e-scooter is used by many people, an e-scooter from a neighbour that can be used, etc.), or availability of company e-scooters (e.g. to grab lunch, to go to a meeting, etc.). Also, false responses cannot be completely ruled out.

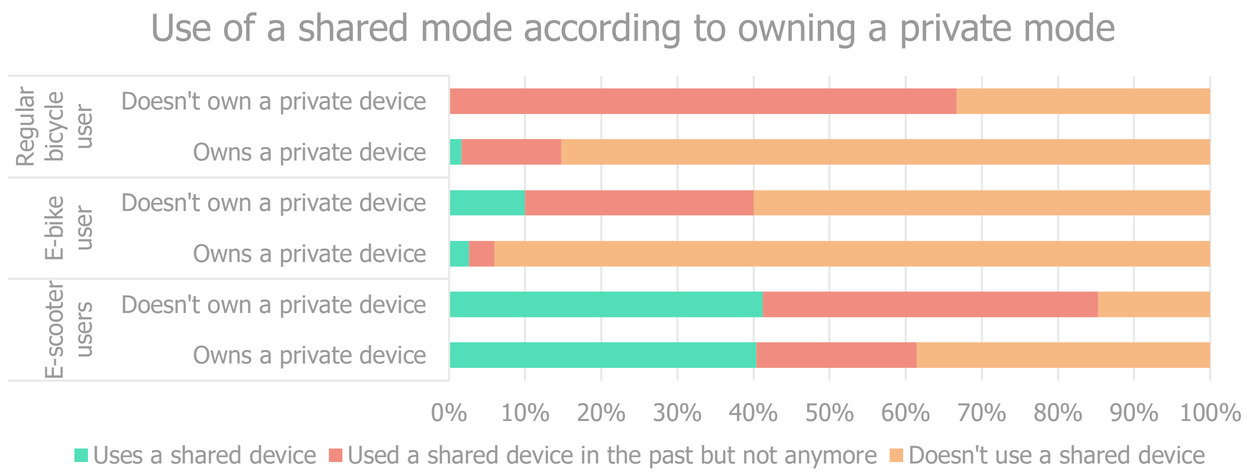


Figure 11: Distribution of using a shared mode when a regular users is not possessing a privately owned mode

A complete overview of the possible uses of an e-scooter is illustrated in figure 12 for the total e-scooter regular user sample.

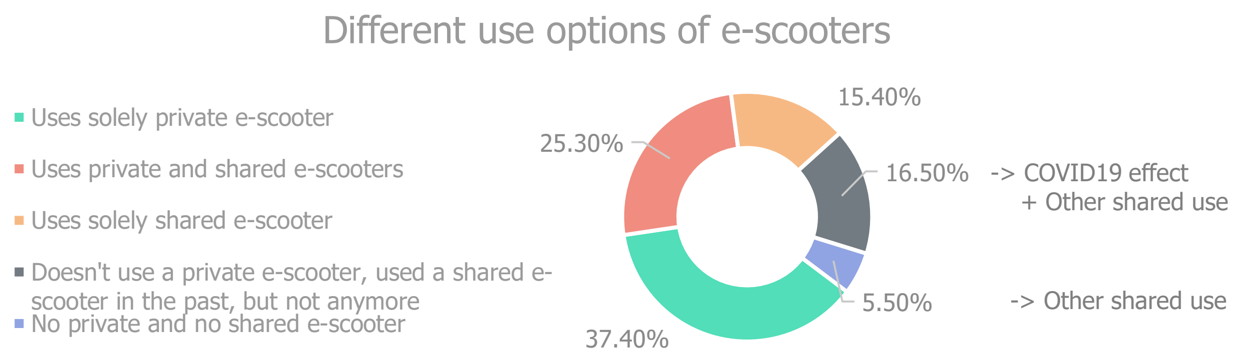


Figure 12: Different ways how regular e-scooter users use an e-scooter

Subsequently, the availability of shared schemes is investigated. It shows in figure 13, according to the regular users, that the availability of shared e-scooters is the highest. Nearly 40% of the regular e-scooter users indicates that they have a shared scheme nearby (compared to 18% for bicycles and 12% for e-bikes). For conventional bicycles, most regular users indicate that the system is not available. The proportion of regular users and non-regular users of e-bikes not knowing if a shared scheme is available is the highest.

In general, most of the non-regular users, indicate not having a shared system available or not knowing if there is one nearby, possibly directly explaining their non-use.

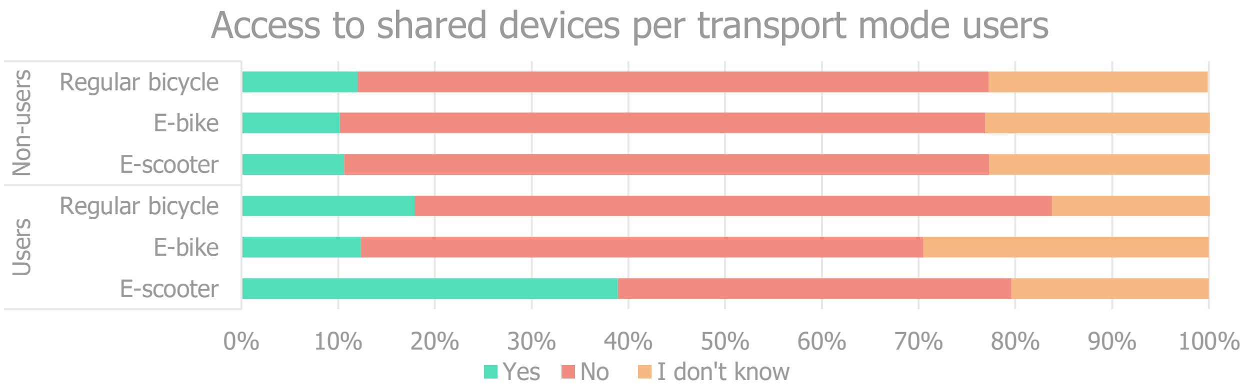


Figure 13: The availability of shared devices for each specific transport mode

Next to shared use, the availability of space to safely store a private e-scooter, e-bike, or conventional bicycle was asked. Figure 14 shows that the storage of these modes is in general possible at home for 88% of the users. The storage of these transport modes at the destination, however, is less often possible (i.e. generally only for 53% of the users). Here, bicycles and e-scooters can be more often stored at the destination compared to e-bikes.

Further, non-regular users more often indicate not being able to store the e-scooter or bike at home or at the destination. This can be a possible explanation for not using the transport mode. It is however also possible that these non-regular users overestimate the necessary place to store one of these modes, or have no charging infrastructure available.

The more compact nature of an e-scooter can explain why this transport mode is easier to store both at home and the destination. The higher price of e-bikes and perceived risk of theft can explain the reported unavailability of storage at the destination, since this often requires lockable bicycle storage spaces.

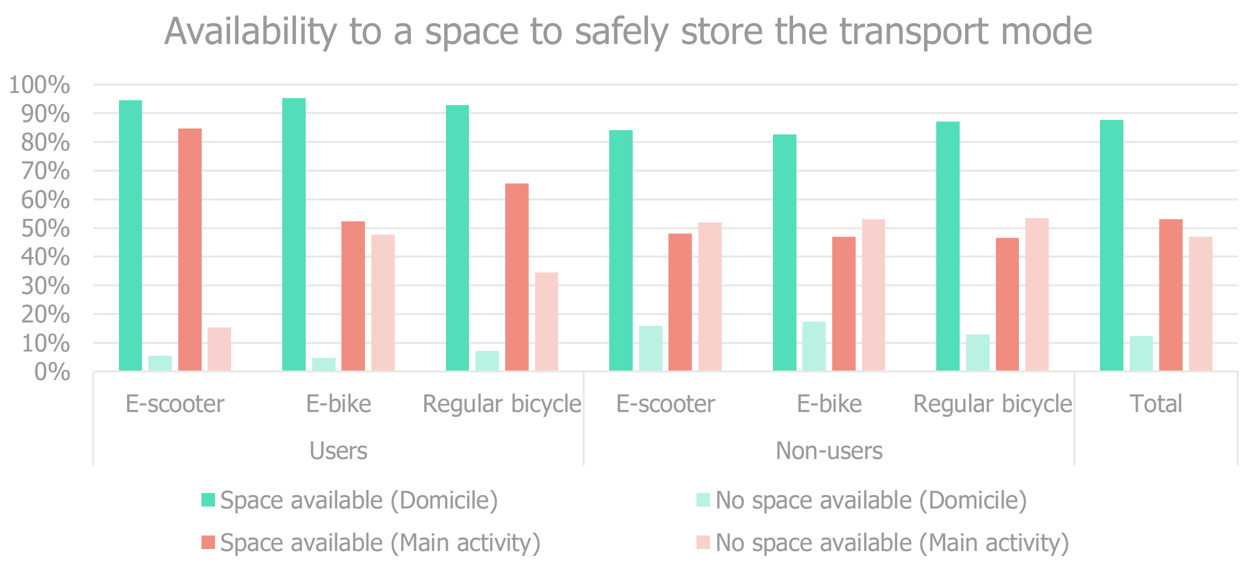


Figure 14: The availability of a space where the transport mode can be safely stored when not in use

This availability of a space statistically significantly differs based on the income and region of the respondent. It was found that the lower the income, the more often respondents indicate not having sufficient space at home or at a main destination to safely store the transport mode. Furthermore, on a regional level, people living in Brussels indicate more often having insufficient space at home to safely store the transport mode, compared to the other regions. More in general, the urbanisation rate plays a large role in this, since it was found that a person living in an urban environment has less often space available to safely store the transport mode.

2.4 Trip characteristics and modal shift

Before looking into the trips characteristics and modal shift, an insight is provided in the possible impact of COVID-19 (and the associated restrictions) on trips. While a large portion of the population hasn't changed their trips with a specific transport mode, it shows in figure 15 that some transport modes gained attractiveness with the COVID-19 restrictions. Especially walking, cycling, and the use of an e-scooter seem to have increased, while the use of public transport decreased. This tends to follow the national trends observed in the mobility barometers[5]. For the other transport modes, both an increase and decrease can be observed, which can be seen as a zero impact or null-effect.

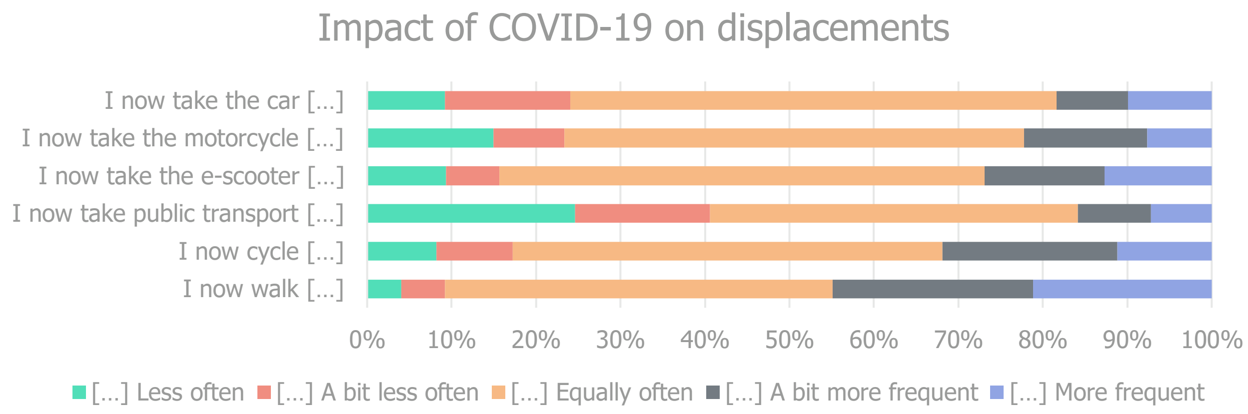


Figure 15: The impact of COVID-19 and its restrictions on the displacements with specific transport modes

Leaving the COVID-effect aside, the use of transport modes can differ according to trip purpose, as shown in figure 16. In general, the car is the most popular transport mode, especially with leisure and other trips (e.g. running errands, picking someone up, going to the doctor, etc.) compared to commuting (i.e. the car is taken on average in 57% of the cases for commuting, while for leisure trips this is 63% and for other trips 69%). Next, cycling and walking are done on average in 10%-15% of the cases with minor differences between the type of trip. Next, public transport is largely taken for commuting trips and in some occasions for leisure trips. E-scooter and motorcycle use is negligible compared to other transport modes.

Further, it was found that people who do not own a car demonstrate a larger variation in the transport modes used, compared to those who own a car. This is logical since they need to perform these trips via different means. This manifests itself in more walking and public transport use.

When the different regular user and non-regular user groups are compared, some differences could be found, that are illustrated in figure 17.

In general, regardless of trip purpose, regular users of a bicycles, e-bikes, and e-scooters less often use the car compared to non-regular users to perform their trips. Public transport is less often used by regular e-bike users compared to the other regular users and non-regular users. The use of an e-bike seems to impact car use as well as public transport use, especially for commuting. For both regular users of e-scooters and conventional bicycles, public transport use is not directly impacted (possibly since these transport modes can complement each other), mainly lowering car use for these regular user groups.

Regular e-scooter users tend to use the bike and e-bike less often than regular users of (electric) bicycles. However, bicycle use within regular e-scooter users is still equally high (or even a bit higher) compared to all non-regular user groups. As a result, it can be stated that the use of an e-scooter does not necessarily has to impact the use of a bicycle.

For walking no differences are found between the different regular users and non-regular users. Both regular users and non-regular users of the different transport modes seem to walk equally often. This also for commuting. It seems that the use of these transport modes doesn't necessarily impacts walking.

[5] The mobility barometer is a quarterly update on mobility in Belgium and accessible here: https://www.mobility.vias.be/en/barometer/

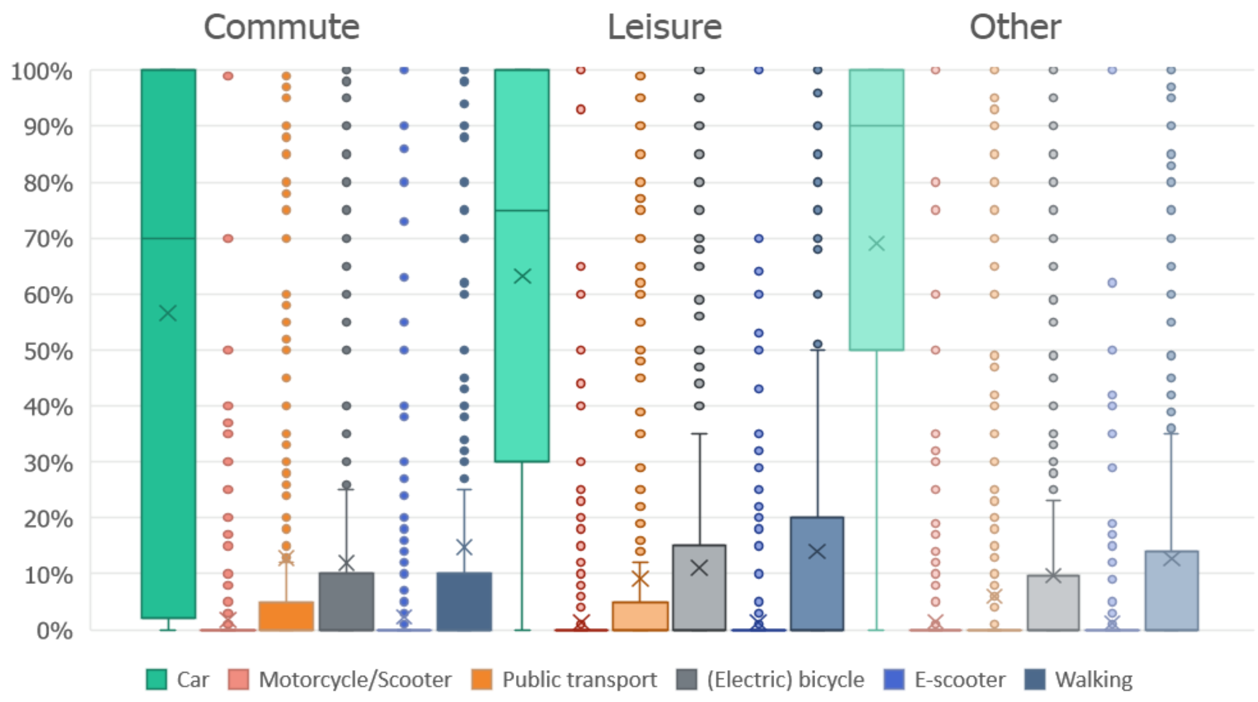


Figure 16: Shares per transport mode for different trip purposes

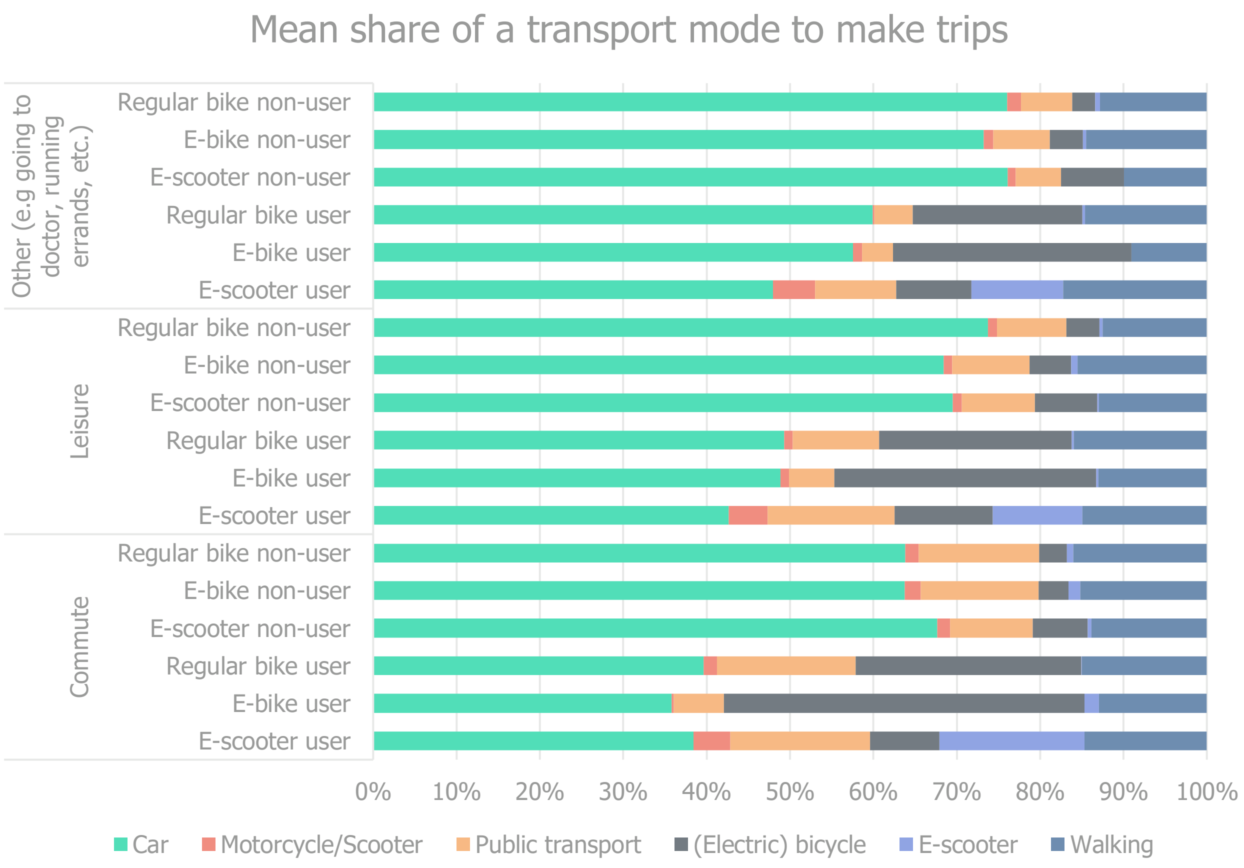


Figure 17: Differences between the regular user and non-regular user groups regarding the share of taking different transport modes

In order to better understand for which trips a possible competition can be present, insights in the travelled distances per transport mode are given in figure 18. A summation of these percentages cannot be made since a person could indicate to perform multiple trip distances for a specific transport mode.

In general, well known trends could be confirmed. For the car, an increase in use is seen, with an increase of the travelled distance. Also can be confirmed that the car is still being used regularly for trips shorter than 5km (i.e. 8% of the people use it for first/last-mile trips, 12% for trips shorten than 2km, and 26% for trips between 2km and 5km). For public transport the full potential, as seen with the car, is present with larger distances. However, to a lower degree in use.

Walking is done very frequently for first/last-mile and short trips, as well as distances up to 5km or even 10km (although these larger distances are more situated in the leisure context). Cycling reaches its full potential for distances between 2km and 5 km but is also frequently done for shorter distances (i.e. first/last mile or shorter than 2km) and even distances up to 10km.

Both the e-scooter and e-bike show their potential on larger distances (i.e. 5-10km) rivalling with the car and public transport. Here the e-scooter has more popularity as well for shorter distances and last-mile trips compared to the e-bike.

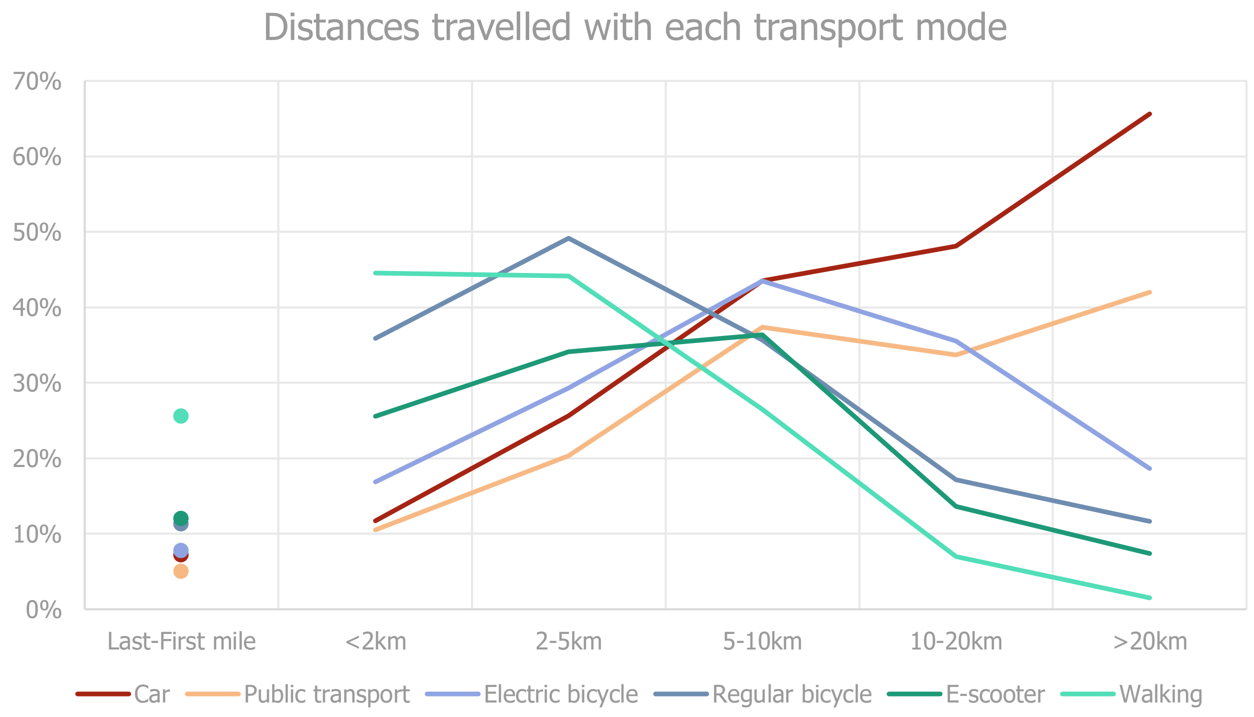


Figure 18: Distances travelled with different transport modes

Based on this added information it can be concluded that e-scooters are used for trips up to 10km, after which the use decreases drastically. Even though these trip lengths are directly comparable to trips with a bicycle, e-scooter trips do not necessarily replace the use of a bicycle (as seen previously in figure 17).

Cycling also exerts an impact on most of the car trips, making the bicycle a direct competitor with the car (especially for shorter distances). Here, e-bikes are rivalling with public transport as well, which is not the case for a conventional bicycle. The fact that e-bikes are used to travel larger distances, has a direct impact on this public transport use as seen in figure 17 (except for very large distances).

2.5 Reasons for choosing an e-scooter or (electric) bicycle

Modal choice is a broad and difficult to grasp concept with multiple motivators. It is important to better understand human behaviour and the reasoning for choosing a specific transport mode. This ensures that possible incentives or countermeasures have the intended effect when a specific transport mode has to be promoted or discouraged. In order to gain more insight into human behaviour, and more specifically behavioural change, many conceptual models been developed over time (e.g. theory of planned behaviour, health belief model, protection motivation theory, etc.). Our questionnaire was set up by using two different behaviour model frameworks, i.e. ERG-theory and Behaviour Change Wheel, to take into account needs of regular users for transport mode choice, as well as factors that hinder non-regular users to take the transport mode.

The ERG theory (i.e. existence, relatedness, and growth theory) tackles mode choice in terms of people trying to fulfil their needs. While this is an important factor in mode choice, it can only partially explain the selection of a specific transport mode, since multiple aspects play a role. This is shown in the figure 19 below, where the factors of the ERG theory plays a role in receiving a certain utility, which impacts mode choice. However, socio-demographic characteristics, Level-of-Service attributes and travel difficulties are also playing a role in this conceptualisation and should be added (Figure 19).

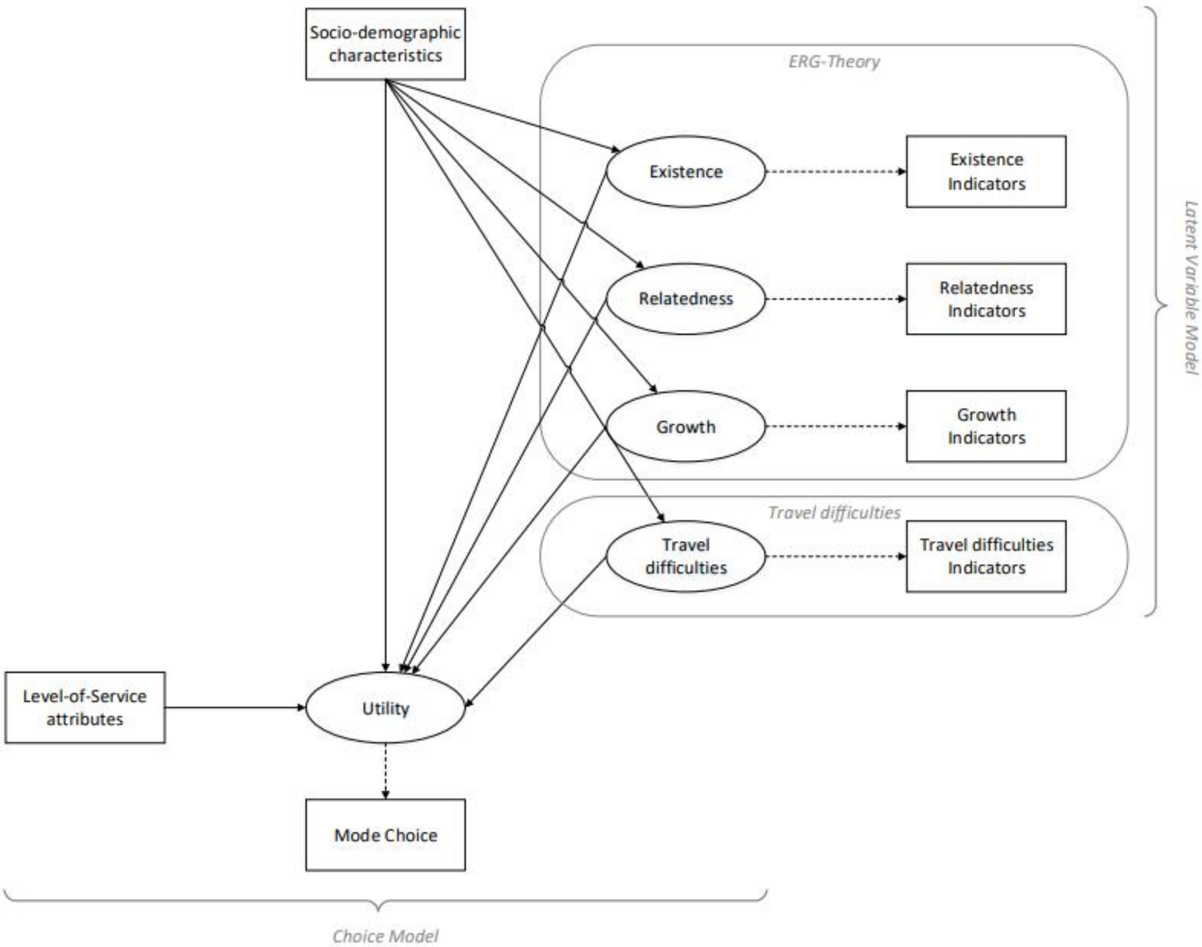


Figure 19: Model framework incorporating the ERG theory of needs, travel difficulties, traditional level-of service attributes, and users' socio-economic characteristics into the mode choice context (Bláfoss Ingvardson et al., 2019)

In order to tackle this shortcoming, the Behaviour Change Wheel concept was used. The Behaviour Change Wheel (BCW) takes underlying constructs into account that are lying inside and outside of the individual, in order to explain why a certain behaviour is performed or not, and which interventions can be used to facilitate or mitigate a behaviour. Through the usage of both models, a better understanding can be achieved of mode choice and travel behaviour.

2.5.1 The fulfilment of needs

The ERG theory was used to determine the underlying factors for choosing one of the transport modes. It is a theory that allows to consider preferences related to how well each mode fulfils the needs of users. The ERG theory is based on Maslow's hierarchical theory of motivation, and is a three-fold conceptualisation of human needs, consisting out of 'Existence', 'Relatedness', and 'Growth' (Bláfoss Ingvardson et al., 2019). The theory states that a chronological sequence is absent, and that people can fulfil their needs independently. This means that lower order needs don't necessarily have to be fulfilled first, before being able to fulfil higher order needs. This gives an interesting dimension in terms of mode choice, since it allows to determine drivers within people to use a certain mode rather than what would prevent them from using it.

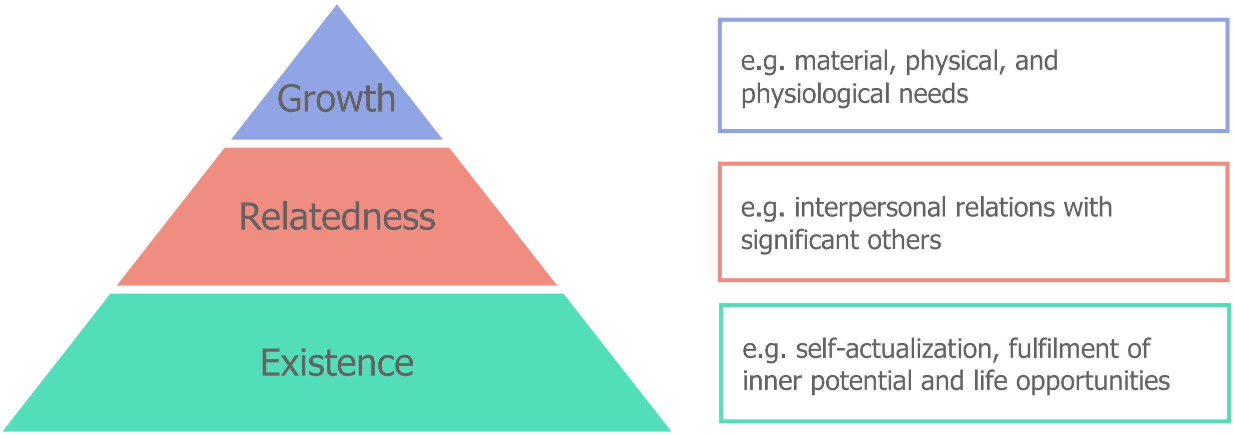


Figure 20: Visual representation of the ERG theory

Based on the ERG theory, multiple items were constructed that tried to capture the different needs from the model (i.e. existence needs, relatedness needs, growth needs). In total 33 items were constructed, visible in table 2, based on available literature. Each respondent had to answer to all these items by means of a five-point likert scale. Afterwards a factor analysis[6] was performed on these items in order to capture the underlying constructs or factors. In total three underlying constructs were found, related to the ERG theory, proving the success of the use of this theory. These constructs consisted out of: 'Utilitarian mobility' (consisting of mostly existence-level needs), 'Subjective norm' (consisting of mostly relatedness-level needs), and 'Attitudes as secondary motivators' (consisting mostly of growth-level needs). A complete overview of these different factors and used items is given in the table below.

A complete overview of the factor analysis is available in the annex.

Table 2: Reasons for taking an e-scooter, e-bike, or conventional bicycle based on the ERG theory level of needs

Utilitarian mobility (consisting of mostly existence-level needs)
– Going to a museum / art exhibition
– Attending after-hours activities (e.g., a language course, music class etc.)
– Meeting your friends during a day
– Going for a professional meeting
– Going out in the evening (e.g. going to dinner, go party, go to the bar, etc.)
– Going for a trip /excursion
– Going to work/school
– Running daily errands (e.g., going to the doctor, going to the hairdresser, going to the pharmacy)
– Picking up take-away food
– Meeting new people
– Spending some quality time with your family
– Making a multimodal journey (combining different transport modes, e.g., taking a bike on the train)
– Doing local groceries (e.g., in the street market, local supermarket)
– Going to a bigger store (e.g., hypermarket, Ikea etc.)

[6] A factor analysis is a statistical technique that reduces a set of variables by extracting all their commonalities into a smaller number of so called 'factors'. It can be seen as a data reduction method for a large set of individual items (TIBCO, n.d.).

Subjective norm (consisting of mostly relatedness-level needs)
– I believe my family/friends would think it is nice that I use it
– I think it becomes trendy to use it
– I believe it allows to impress friends, co-workers, family
– I believe it gives a kind of social prestige/benefit to use it
– I believe it allows to demonstrate your opinion/beliefs
– I believe that people who use it belong to a certain (social) group/movement
Attitudes as secondary motivators (consisting mostly of growth-level needs)
– I believe it is good for the environment
– I believe is better for my health to use this rather than other transport modes
– I believe it is good for my health
– I believe it helps to improve the situation in cities (congestion, pollution, noise etc.)
– I think it is well perceived by the society to use it
– I believe it allows to contribute to a better society
– I find it gives a good feeling to use it (adrenaline, freedom etc.),
– I believe it is cheaper than other transport modes
– Using it to clear my head and stimulate productivity
– I believe is easier to park / does not require parking
– I believe it offers more flexibility than other transport modes

The factor 'Utilitarian mobility' refers to the aspect of using a transport mode in order to perform an activity or use it for practical considerations (e.g. going to a store, meeting with friends, running errands, performing after-hour activities, etc.). It relates to the existence-level of needs from the ERG theory, since the items related to utilitarian mobility all relate to the fulfilment of basic needs, to survive or encompass physiological wellbeing.

The factor 'Subjective norm' takes into account the belief about whether or not a person or group of people approves or disapproves taking the specific transport mode, impacting the use of that transport mode. It refers to taking a specific transport mode in order to comply with the subjective norm (e.g. since they believe it allows to impress others, since they believe it gives social prestige, etc.). This factor corresponds with the relatedness-level of needs from the ERG theory, since it relates to interpersonal and social relationships.

The factor 'Attitudes as secondary motivators' refers to higher order (e.g. believing it is good for the environment, believing it is good for health, etc.). This factor relates to the growth-level needs of the ERG theory that implies an inner desire for personal development.

In order to better understand which underlying reasons can be more important for taking a specific transport mode, differences between the transport modes were sought. Figure 21 gives an overview of the different average scores, received through the factor analysis for e-scooters, e-bikes, and conventional bicycles for each of the different underlying reasons/fulfilment of needs. In this figure, more focus is laid on the regular users compared to the non-regular users, since more attention is given to the reasoning why regular users take one of these transport modes.

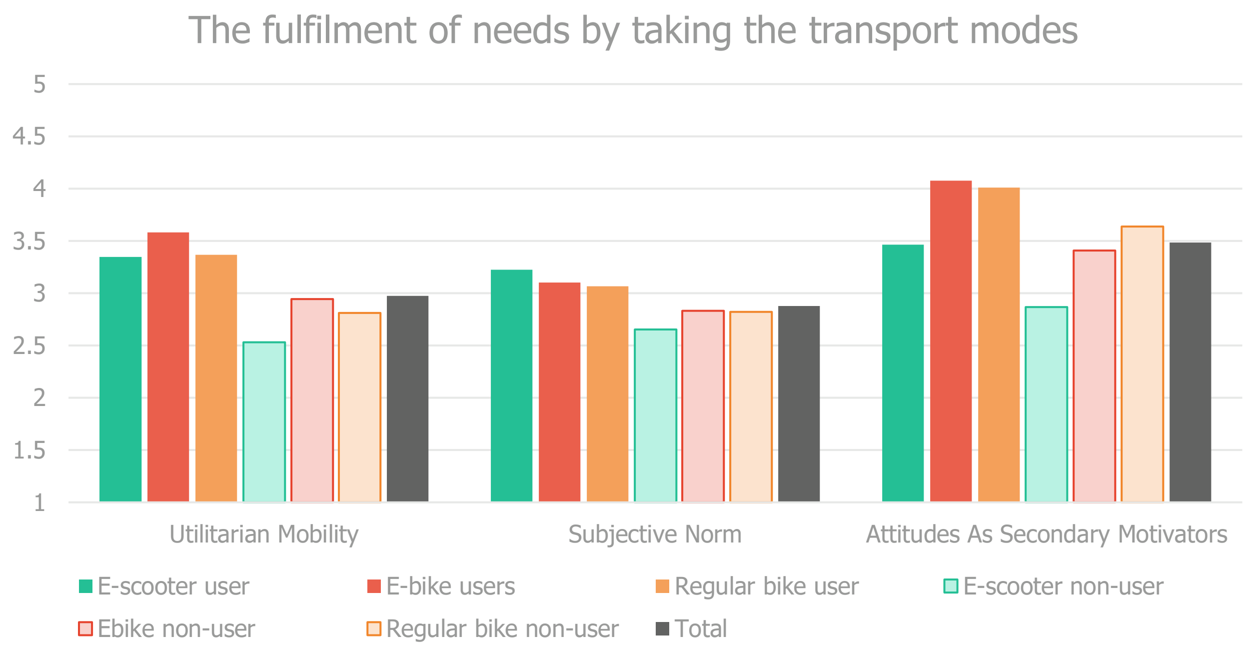


Figure 21: Reasons behind taking an e-scooter, e-bike, or conventional bicycle, based on the ERG level of needs

Taking the higher scores for attitudes as secondary motivators into account (i.e. highest level of needs), it appears that higher order needs play the most important role in the mode choice. This is not only true for regular users, but also for non-regular users. This shows that certain transport modes carry a notion of being more than just a simple way of getting from point A to point B. This can be stated since more altruistic reasons play an important role, as well as catalysts to be able to do more in life. On this level, regular users of e-bikes and regular users of conventional bicycles score the highest which can potentially be explained by the fact that an e-bike is the most suitable alternative to the car. Hence, it provides a rather easy way of moving while at the same time providing a significant feeling of self-development, contributing to higher. Bikes and e-bikes are more coherent in the impact they have compared to e-scooters, which can be explained by the limited evidence on e-scooters and their impact on the planet. This can explain the lower scoring seen for regular e-scooter users compared to regular bicycle users.

The second most important reason for taking one of these different transport modes is the aspect of utilitarian mobility (i.e. basic needs). The decision to take an e-scooter, e-bike, or conventional bicycle is thus only in the second place determined based on the basic needs, leading to a derived demand, and in its turn to mobility. Out of all modes, regular e-bike users score the highest and tend to use an e-bike more frequently to fulfil basic (mobility) needs. Since an e-bike makes use of a conventional bicycle platform (more luggage possibilities than an e-scooter, while having the same benefits as a conventional bicycle), while having additional motorized support, it is therefore possibly more suitable to fulfil basic needs compared to the conventional bicycle and e-scooter. It can be seen that e-scooters and conventional bicycles are scoring equally high on fulfilling the basic needs. This in contrast with the belief that e-scooters are the least optimal to fulfil basic (mobility) needs due to their limited loading capacity, lack of possibilities to store the private mode of transport in public areas (e.g. bicycle racks are often not suitable to safely store an e-scooter), etc. Also, is shown that regular users notice more benefits of utility from any of the transport modes, compared to the non-regular users. This could mean that a person starts to appreciate the mode (and seeing the perks) after use of the device, while non-regular users may have more difficulties in seeing these benefits or possibilities to fulfil these basic needs.

With regards to the subjective norm, it shows that this subjective norm is the least important reason to determine the choice for a certain transport mode, although still being a relevant factor in transport mode choice. It appears that the social perception of a given transport mode is almost equal among all transport mode users, only showing major differences between regular users and non-regular users. Regular users of these different transport modes seems to pay more attention to how people perceive them, which is the highest among e-scooter users (e.g. a desire to impress, being seen as a gadget person, innovator, trying something new that is cool etc.). The overall score suggests a desire of belonging to a community (e.g. "us" bikers vs. "you" car drivers, "us" using new mobility vs. "your" old fashion way of moving) or being able to express themselves or their beliefs. Non-regular users on the other hand seem to be more subjective to social pressure (i.e. not having tried it yet so relying on beliefs of others) leading to a lower scoring. Further, it can be observed that non-regular e-scooter users perceive the e-scooter as the least able in fulfilling social aspects needs, indicating not caring much about what others think or how the e-scooter could improve their social prestige. However, attention is needed since we are talking about normative beliefs (i.e. what a person thinks that other people think or believe) and not the actual social perception of people.

In general, it seems that especially e-bikes and conventional bicycles fulfill the highest order needs (i.e. attitudes as secondary motivators). In addition, e-bikes are also seen as more suitable in fulfilling basic needs (i.e. utilitarian mobility) compared to e-scooters and conventional bicycles. On the other hand, regular e-scooter users tend to take all of these aspects equally into account. This difference with conventional bicycles and e-bikes can possibly be explained by the lack of knowledge and lack of market maturity of e-scooters impacting the attitude, or seeing this transport mode in a broader picture to not only fulfil a specific type of need. Subsequently, a bigger variation is always present between regular users and non-regular users of the different transport modes, with e-scooters showing the biggest variation. Overall, regular users are being more in favour compared to non-regular users, which can potentially mean that trying out an e-scooter makes people acknowledge the positive aspects of the transport mode, while non-regular users are staying more in the dark relying on opinions of others (i.e. which can explain the low scoring on subjective norm).

Lastly, when looking at people with a disability, data shows that the importance of attitudes as secondary motivator is rated lower compared to people without a disability. Further, the subjective norm is rated slightly higher compared to those without a disability. The utilitarian reasons stay equally important. A possible explanation lies in more difficulties in completing basic needs, leading to less interest and time for higher order needs. This shows again the need for further research for this specific target group.

2.5.2 Prerequisites of behaviour and behavioural change

The BCW Focusses on underlying constructs of behaviour, trying to explain why certain people are performing a specific behaviour or not, and which behaviour change intervention can be used to target the desired behaviour. Behaviour change interventions are important. They can be used to promote healthy lifestyles and adequate behaviour (e.g. taking an active transport mode instead of the car). However, in order to identify an effective type of intervention, a full range of options needs to be available together with a rational system for selecting the right options among them. This should be supported by a model of behaviour, without overlooking certain important influences (e.g. the Theory of Planned Behaviour and Health Belief Model are good in explaining certain behaviours, but they do not address certain important roles, such as impulsivity, habit, self-control, etc.) (Michie et al., 2011).

In order to tackle this problem, and to get an integral behaviour intervention model, the COM-B model was developed. Here, the most important components that can explain current behaviour were identified that are necessary and sufficient prerequisites for the performance of a specified volitional behaviour. These components were 'capability', 'opportunity', and 'motivation'. The arrows in the model represent a potential influence between components in the system. The causal links within the system can work to reduce or amplify the effect of particular interventions on one or more components in the behaviour system, leading to changes elsewhere (Michie et al., 2011).

- **Capability:** "the individual's psychological and physical capacity to engage in the activity concerned, including having the necessary knowledge and skills."
- **Opportunity:** "the factors laying outside the individual that make the behaviour possible or prompt it."
- **Motivation:** "all brain processes that energize and direct behaviour, not just goals and conscious decision-making. It includes habitual processes, emotional responding, as well as analytical decision-making."

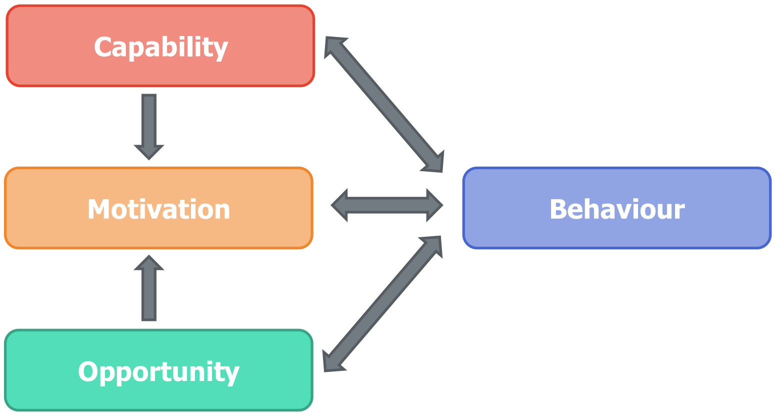


Figure 22: COM-B model framework, on which the behavioural change wheel is based (Michie et al., 2011)

With the COM-B model as a basis, **the behaviour change wheel** (BCW) was developed, incorporating the **sources of behaviour, together with interventions and policy measures**. Around the hub (showing the COM-B components) nine intervention functions were placed aimed at addressing deficits in one or more of these conditions. Around this, seven categories of policy were placed that could enable those interventions to occur (Michie et al., 2011). The model can be seen in figure 23, with definitions of the terms displayed in table 3 (applied on e-scooter use).

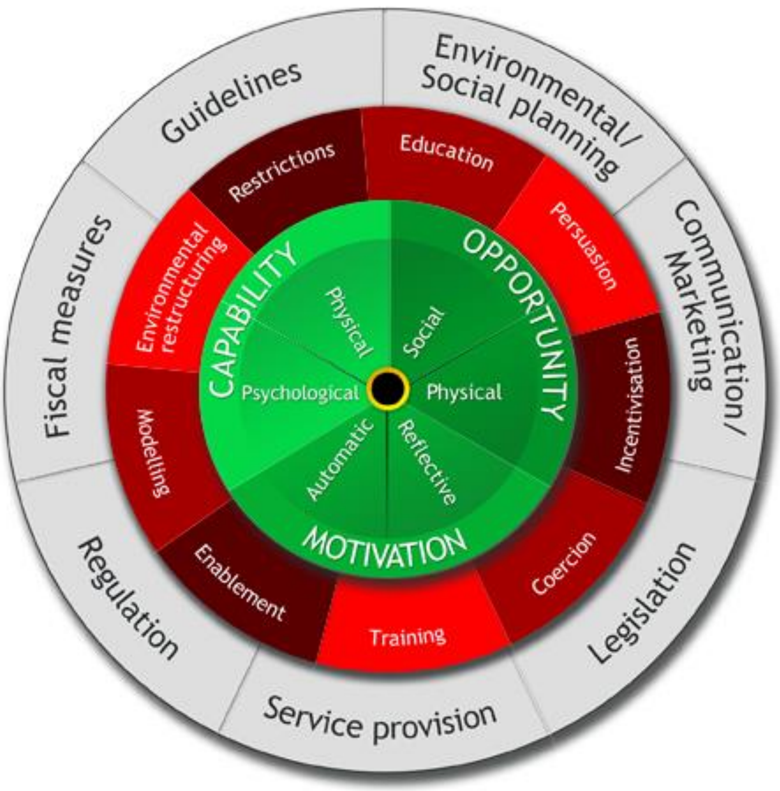


Figure 23: The Behaviour Change Wheel framework (Michie et al., 2011)

Table 3: Definitions of interventions and policies with examples applied to e-scooters (Michie et al., 2011)

Interventions	Definition	Examples
Education	Increasing knowledge or understanding.	Providing information on how to safely use an e-scooter.
Persuasion	Using communication to induce positive or negative feelings or to stimulate action.	Using campaigns to show the benefits of an e-scooter in cohesion with public transport to reduce car use.
Incentivisation	Creating an expectation of a reward.	Include the e-scooter in the bicycle allowance scheme.
Coercion	Creating an expectation of a punishment or cost.	Increasing the likelihood of being fined for driving to quickly in pedestrian zones.
Training	Imparting skills.	Invest in basic training programs in schools and companies to safely use an e-scooter comparable to a bicycle exam.
Restriction	Using rules to increase the target behaviour by reducing the opportunity to engage in competing behaviours.	Obliging that e-scooter users have to get off their e-scooter and walk with the scooter in hand in a pedestrian zone.
Environmental restructuring	Changing the physical or social context.	Give priority to vulnerable road users instead of fixating on fluidity of traffic.
Modelling	Providing an example for people to aspire to or imitate.	Using tv drama scenes with an e-scooter accident to reduce unwanted behaviour.
Enablement	Increasing means/reducing barriers to increase capability or opportunity[1].	Making a standardisation possible to fix an e-scooter to a wheel chair.
Policies	**Definition**	**Examples**
Communication/ marketing	Using print, electronic, telephonic, or broadcast media.	Conducting mass media campaigns.
Guidelines	Creating documents that recommend or mandate practice. This includes all changes to service provision.	Creating a document that helps companies to recommend e-scooter usage if it suits their practice.
Fiscal	Using the tax system to reduce or increase the financial cost.	Giving fiscal benefits to companies that replace car usage by e-scooters or multi-modal solutions including an e-scooter.
Regulation	Establishing rules or principles of behaviour or practice.	Establishing voluntary agreements between e-scooter users and companies to wear a helmet when using the e-scooter.
Legislation	Making or changing laws.	Creating a new legislation that treats the vehicle categorisation of micromobility devices in relation to other vehicles.
Environmental/ social planning	Designing and/or controlling the physical or social environment.	Using different pavement in areas where e-scooters are unwanted.
Service provision	Delivering a service.	Facilitating repair shops for e-scooters in railway stations.

[1]Capability beyond education and training, opportunity beyond environmental restructuring.

The behavioural change wheel makes it possible to determine interventions and policy categories based on current and desired behaviour. However, it is needed to determine the appropriate intervention or policy category in order to avoid a null-effect (e.g. it is not beneficial to focus on fiscal treatments to increase e-scooter usage, if the infrastructure is unsafe). In order to see which intervention functions (i.e. the inner layer around the hub) and policy categories (i.e. the outer layer around the hub) can be linked to the sources of behaviour (i.e. the hub of the wheel), table 4 and table 5 can be used.

Table 4: Links between the intervention functions (inner ring around the hub of BCW) and the sources of behaviour (the hub of BCW) (Michie et al., 2011)

		Intervention functions								
		Education	Persuasion	Incentivisation	Coercion	Training	Restriction	Environmental restructuring	Modelling	Enablement
Sources of behaviour	Physical capability					✓				✓
	Psychological capability	✓				✓				✓
	Physical opportunity	✓	✓	✓	✓					
	Social opportunity		✓	✓	✓			✓	✓	✓
	Reflective motivation						✓	✓		✓
	Automatic motivation						✓	✓		✓

Table 5: Links between the intervention functions (inner ring around the hub of BCW) and the policy categories (outer ring of BCW) (Michie et al., 2011)

		Intervention functions								
		Education	Persuasion	Incentivisation	Coercion	Training	Restriction	Environmental restructuring	Modelling	Enablement
Policy categories	Communication/Marketing	✓	✓	✓	✓				✓	
	Guidelines	✓	✓	✓	✓	✓	✓	✓		✓
	Fiscal			✓	✓	✓		✓		✓
	Regulation	✓	✓	✓	✓	✓	✓	✓		✓
	Legislation	✓	✓	✓	✓	✓	✓	✓		✓
	Environmental/social planning							✓		✓
	Service provision	✓	✓	✓	✓	✓			✓	✓

In order to include the behavioural change wheel in the questionnaire, multiple items were constructed. A total of 31 items were constructed, of which 25 were kept after two distinctive factor and reliability analyses. Table 6 below gives an overview of the 25 items and corresponding COM-B components. A detailed overview of all 31 items can be found in the annex.

Table 6: Questionnaire items that were applicable for the behavioural change wheel framework

COM-B model items
In order for me to use the e-scooter (more often) I […]
Physical capability
[…] would need to have more physical endurance to not be fatigued immediately. (e.g. develop greater stamina to not be exhausted after a ride)
[…] would need to be physically stronger (e.g. build up stronger legs to be able to conquer a steep hill, or be stronger to carry it in the train)
[…] would need to find a solution to overcome physical limitations (e.g. get around problems about seating or standing position on the transport mode)
[…] would have to have better skills to operate the device (e.g. follow a practical training to safely use the device)
Psychological capability
[…] would have to have more mental endurance to make sure that I keep focussed while using this transport mode. (e.g. stay focussed in a city centre with dense traffic after a 20min ride)
[…] would need to develop more confidence in using the device (e.g. be convinced that I can easily reach my destination)
[…] would need to know more about the benefits of this transport mode (e.g. know how it contributes to greener mobility or improved living quality, or knowing how much time it would save me if I used it, etc.)
[…] would need to know more background info about how the device works. (e.g. how to charge it, how fast it goes, etc.)
Physical opportunity
[…] would have to have better maintained shared devices so that I would want to use it more (e.g. replace damaged scooters, better cleaned, etc.)
[…] would need to have the transport mode more accessible/available (e.g. need to have a personal device or should be able to make use of a shared device)
[…] would need to have more money to use this transport mode
[…] would need to have an adapted device in order for me to be able to use it (e.g. a different seat mounted, etc.)
[…] would need to have more time to use this transport mode.
[…] would have to have some facilities at my main activity that make it able for me to use it (e.g. ability to shower, ability to charge it, etc.)
Social opportunity
[…] would have to have more support from others to use the transport mode (e.g. have friends that support me and don't laugh with me for using it)
[…] would need to feel that I'm part of a community (e.g. live in a city where most people use it as a transport mode as part of their life)
[…] would need to have more people in my close environment around me that use the transport mode (e.g. colleagues that use the transport mode, my family, my friends)
[…] would need to have more triggers to be prompted to use the transport mode (e.g. someone that passes me every morning and is faster at work than me, other people that use it look more healthy, etc.)
Reflective motivation
[…] would need to feel that it is safe to use (e.g. having read somewhere that it is a safe transport mode)
[…] would need to make a plan to use the transport mode (e.g. think about the alternative routes I can take, plan my trip better in advance)
[…] would need to feel that it is natural for me to use it (i.e. I feel bad if I am using a different transport mode, while knowing the e-scooter would have been better).
[…] would have to belief that I contribute to environmental sustainability (e.g. I would need to be convinced that using this transport mode is good for the environment)
Automatic motivation
[…] would need to get fun out of using this mode (e.g. feel happy that I don't take the polluting car or get relaxed from the morning air)
[…] would automatically need to feel that I want to use this mode (e.g. automatically think of using this mode since I like physical activity or like the fresh morning air, etc.))
[…] would have to develop a habit of using the transport mode (e.g. would need to make a habit of going with this mode to the station)
[…] would need to overcome negative feelings that automatically seep in (e.g. overcome the automatic thought that it is unsafe to use this transport mode, because I saw someone having an accident or falling).

Firstly, looking at the general results in figure 24, motivational aspects play the most important role in not taking one of these transport modes. This is the case for both the automatic and reflective motivation. Subsequently, the physical opportunity is also an important factor for impeding their use. Especially the physical aspects that lie outside the individual (e.g. time, money, accessibility, specific facilities, etc.) are showing a higher score.

Both the physical and psychological capability are also impeding the behaviour, be it to a lesser extent. Physical limitations (e.g. easily fatigued, strength, skills, etc.), as well as psychological limitations (e.g. low mental strength, low confidence, lack of knowledge, etc.) are not the main obstructor for taking one of these transport modes, although still being impeding factors. It is possible that the full or partial motorised support from 2 out of 3 transport modes plays a role in this.

Lastly the social opportunity is having the lowest impact on the usage of these devices. The support or behaviour of others isn't an important factor for the use of these transport modes. This confirms the findings of the ERG theory previously discussed, where it was found that the need to comply with the subjective norm was the least important need fulfiller for mode choice (especially for non-regular users).

Further, the general results also show that people with a disability (any kind) rate the capability and opportunity factors higher compared to those that do not have a disability. The motivation doesn't differ. This shows that people with a disability encounter more difficulties, with regards to both the physical and psychological capability as well as the physical and social opportunity, impacting the use of these transport modes.

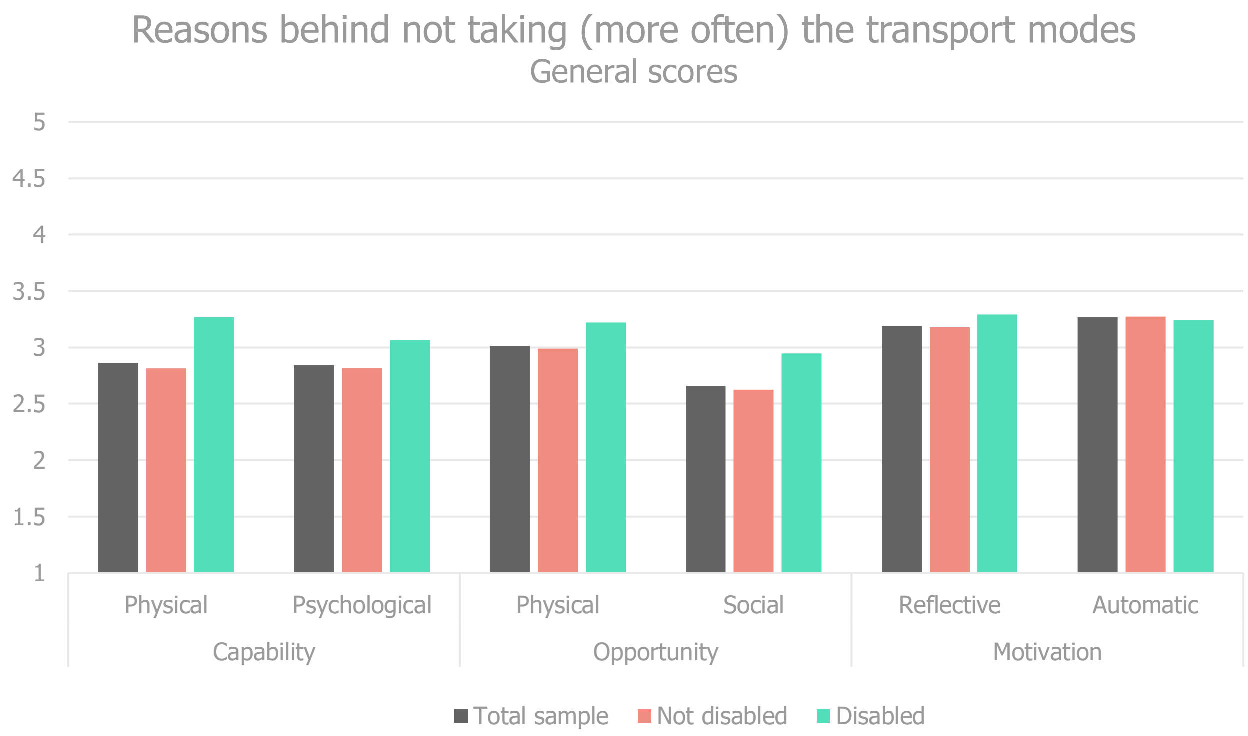


Figure 24: General scores on the sources of behaviour that indicate the reasons for not taking the transport mode

Subsequently, a differentiation is made between the different transport modes in figure 25. In this figure, more focus is laid on the non-regular users compared to the regular users, since a special interest is present for the factors that hinder non-regular users to take the transport mode. The scores of regular users are still made visible to see how they rate these aspects from a user perspective.

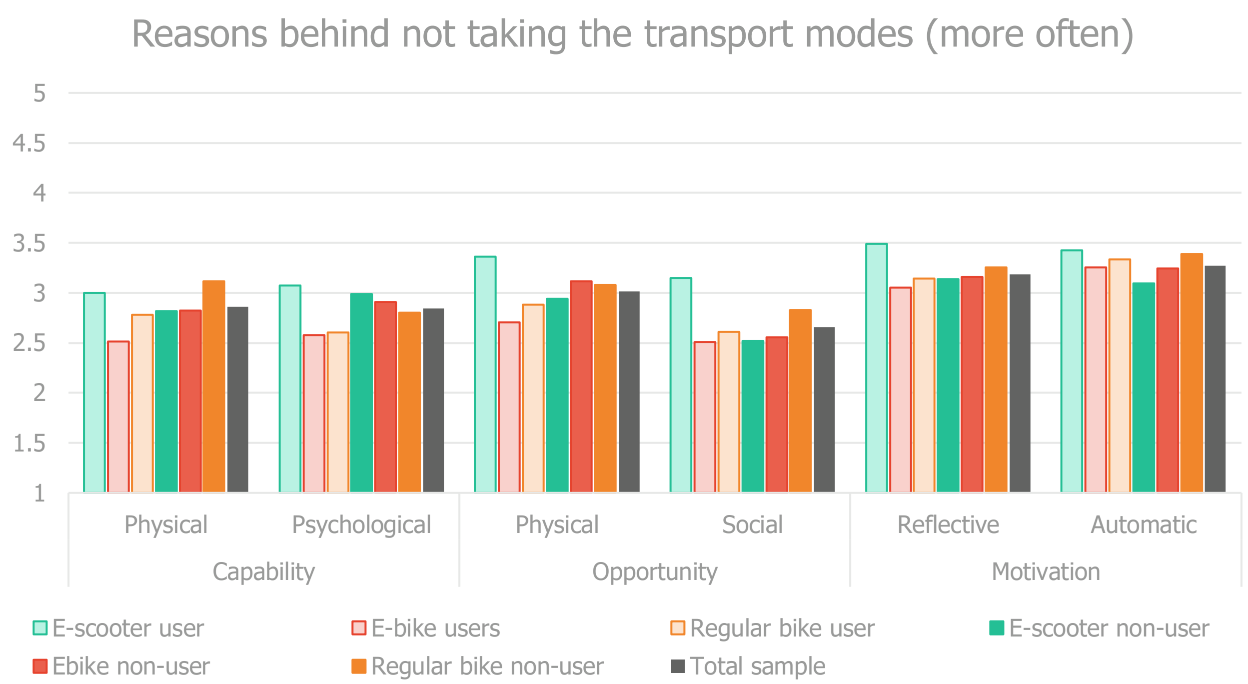


Figure 25: Differentiation between the different regular users and non-regular users on the sources of behaviour that indicate the reasons for not taking the transport mode

In general, the non-regular users of a specific transport mode give higher scores, compared to the regular users of the same transport mode. This means, that non-regular users indicate to encounter more difficulties to use the specific transport mode, which off course leads to the non-usage of that transport mode. This was to be expected, since people who already use a transport mode, already largely overcame these shortcomings. However, their score is not zero, since every regular user probably still encounters difficulties to use the transport mode more often (e.g. regardless of how often a bicycle is taken, still having a need for more time, or, not wanting to ride a bicycle in the rain).

An exception is visible with regular e-scooter users that show higher scores on all sources of behaviour. This could mean that the regular e-scooter users in this dataset are generally rating these aspects more strictly. On the other hand, it is also possible that regular e-scooter users still encounter quite some difficulties for using the transport mode, even while already using it. The higher number of regular e-scooter users that are disabled didn't have an influence here.

Focussing on the factor 'motivation', it becomes visible that the 'automatic motivation' is the most important threshold for all modes hindering their use. Here, the non-regular users of bicycles indicate that it hinders potential use more compared to non-regular users of e-scooters. A difference with non-regular users of e-bikes was absent. Put in practice, it means that non-regular users of conventional bicycles less often have a habit of thinking about using a bicycle, have less positive feelings towards a bicycle, or don't automatically get fun from using it, which leads to not using a bicycle. This in contrast to the non-regular users of e-scooters where this plays a smaller role.

No differences were present between the regular users and non-regular users, as well as the different transport modes, for the 'reflective motivation'. However, it is still one of the most important factors that hinders the use, next to the 'automatic motivation'. Put in practice, it means that both regular users and non-regular users of the different modes aren't dedicating specific reasoning to use the transport mode, therefor leading to less or no use of the transport mode (e.g. forgetting about the recurring traffic jam as a reason to now chose the bicycle or e-scooter as an alternative).

Next, 'physical opportunity' plays an important influence, but differences between the transport modes were absent (statistically speaking), mainly showing differences between regular users and non-regular users (regardless of the transport mode). The 'physical opportunity', that can hinder the use of these transport modes, doesn't differ based on the transport mode itself (in terms of availability, time, budget, parking facilities, etc.). Put in practice, it means that e-scooters aren't seen as less or more available, more expensive, more time consuming, etc. than bicycles or electric bicycles according to the non-regular users. This is consistent with the previous findings were most of the non-regular users indicated not having a shared system available or not knowing if there is one nearby.

'Physical capability' and 'psychological capability' seem to play an equally important role in terms of hindering the use of one of the transport modes. It stands out that non-regular users of conventional bicycles score the physical capability drastically higher as a reason that hinders the use of a bicycle, compared to the non-regular users of the other transport modes. Since cycling with a conventional bicycle requires more physical effort compared to using an e-scooter, and to some extent e-bikes when the length of the trip is ignored, it is quite logical that this is seen as a limiting factor for taking a bicycle. In fact, the 'physical capability' is even more hindering compared to the 'physical opportunity' for taking a bicycle, that in general was seen as a more hindering factor over all transport modes. E-scooters and e-bikes also portray difficulties in relation to the 'physical capability', but to a lesser extent. This can be explained by the powered support of these devices.

With regards to the 'psychological capability', statistically significant differences between the different modes were absent, again mainly showing differences between regular users and non-regular users. This indicates that the psychological capability, that can hinder the use of these transport modes, doesn't differ based on the transport mode itself (in terms of mental strength, mental endurance, knowledge, etc.). Put in practice, it means that e-scooters aren't seen as less or more mentally tiresome, more complicated, etc. than bicycles or electric bicycles according to the non-regular users. Non-regular users find that, in order to use any of these modes, more knowledge, mental endurance, mental strength etc. can be beneficial to start using it. To add to this, a correlation was made with physical activity performed by the respondent on a weekly basis. This showed that people who perform more physical activity, not only see 'physical capability' but also 'psychological capability', as a less important hindering factor to use these transport modes.

Lastly, 'social opportunity' hinders the use of these transport modes the least. Here non -regular users of bicycles score the 'social opportunity' again higher as a reason that hinders the use of a bicycle, compared to the non-regular users of the other transport modes. Between the other transport modes no differences could be observed. Put in practice, this indicates that in order to cycle these non-regular users would like to have more support from others or would like to see more people using it before using it themselves. This is really not the case for the other transport modes. However, can support from others still prompt the use of the other modes as well, being it to a lower extent.

2.5.3 Summary of reasons and underlying factors for mode choice

When both models and findings are being summarised, the results show that the attitudes as secondary motivators are playing the most important role nowadays in mode choice (e.g. believing it is good for the environment, believing it is good for health, etc.). Here the conventional bicycle and e-bike are scoring better than the e-scooter. This means that the conventional bicycle and e-bike are being a better commodity to fulfil these higher order needs. E-scooters seem to fulfil these higher order needs to a lesser extent, possibly due to a negative connotation around them.

The utilitarian aspect of these transport modes is the second most important reason for mode choice (e.g. doing groceries, going for a meeting, meeting with friends, etc.). Especially the conventional bicycle and e-bike are scoring better on this aspect. This means that the conventional bicycle and e-bike are seen to contribute more to the specific needs for utilitarian trips (possibly being an alternative for the car). On the other hand, e-scooters seems to score less on this aspect, possibly due to the lesser possibilities to use it as an independent transport mode (i.e. no storage possible in bicycle storage, less luggage options, etc.).

The subjective norm is the least important aspect in order to choose for a bicycle, e-bike, or e-scooter (i.e. what a person believes that another person might think). Regular users of these transport modes (especially regular e-scooter users), take this subjective norm more into account compared to non-regular users, but it remains the least important reason. Furthermore, this social aspect is also not really hindering the use of these transport modes. The opinion of others, seeing others use the transport mode, and support from others - or the lack there off- isn't immediately hindering people to use it. The only exception here are bicycles, that seem to be influenced a bit more by this social aspect compared to e-scooters and e-bikes.

In classic transport theories, travel demand is derived, suggesting that utilitarian aspects are playing a key role in transport mode choice. However, it is now found that certain transport modes can be more associated with higher order feelings (in this case especially the conventional bicycle and e-bike), being a more important reason to chose for the specific transport mode. It highlights that some transport modes carry a notion of being more than just a simple way of getting from point A to point B.

In order to use these transport modes, one has to be capable in doing so. This does not only consist out of a physical capability (i.e. having enough physical strength, endurance, or skills) but also a psychological capability (e.g. mental endurance, mental strength, or knowledge). More physically demanding transport modes, like the conventional bicycle, seem to really feel the impact in use by this physical capability. It is an important reason why people are not using a bicycle. This in contrast to an e-scooter or e-bike that doesn't require as much physical effort (for an e-bike this is largely dependent on the length of the trip). On the other hand, the psychological capability is an important reason for not taking a transport mode. Here differences between the transport modes are largely absent. In fact, a person's ability to have enough concentration, focus, and knowledge is playing an important role for all of these transport modes. Not to be underestimated, physical activity plays an important role, since it was found that people who more regularly perform physical activity also have less constraints in terms of both their physical and psychological capability.

A physical opportunity also has to be present in order to use the transport mode (e.g. shared transport mode available, showers at work, more time needed, etc.). It seems that this physical opportunity is in fact an important reason why these transport modes aren't used. No difference is observed between the different transport modes. It means that non-regular users find that, in order to use any of these modes, more time is needed, more money is needed, more availability is needed, etc.

Lastly, motivation is the most important factor, impacting the use of these transport modes. Reflective motivation is often a problem indicated by non-regular users. Reflecting and having a thorough reasoning for taking a transport mode seems to be a difficulty. Differences between the transport modes were absent. On the other hand, the automatic motivation is also limiting the choice to take these transport modes. Habitual behaviour and automatic thoughts and feelings, are sometimes absent or difficult to form. This is even more the case in terms of conventional bicycles and e-bikes compared to e-scooters. Non-regular users of conventional bicycles, and to some extent e-bikes, less often have a bicycle naturally coming to their minds while thinking of a trip, have less positive feelings towards a bicycle, or don't automatically get fun from using it, which leads to not using a bicycle. This is also the case for e-scooters, but to a lesser extent.

Only if all of these aspects are considered, a decent understanding can be formed to facilitate the use of these transport modes. The ERG theory and Behaviour Change Wheel (grasping the concepts of travel difficulties, level-of-service attributes, and to some extent socio-demographic characteristics) were able to collect this information. It shows that the reasoning behind taking a transport mode is a difficult to grasp concept. To illustrate this difficulty, an own interpretation is made on the framework designed by Bláfoss Ingvardson et al. (2019) in figure 26.

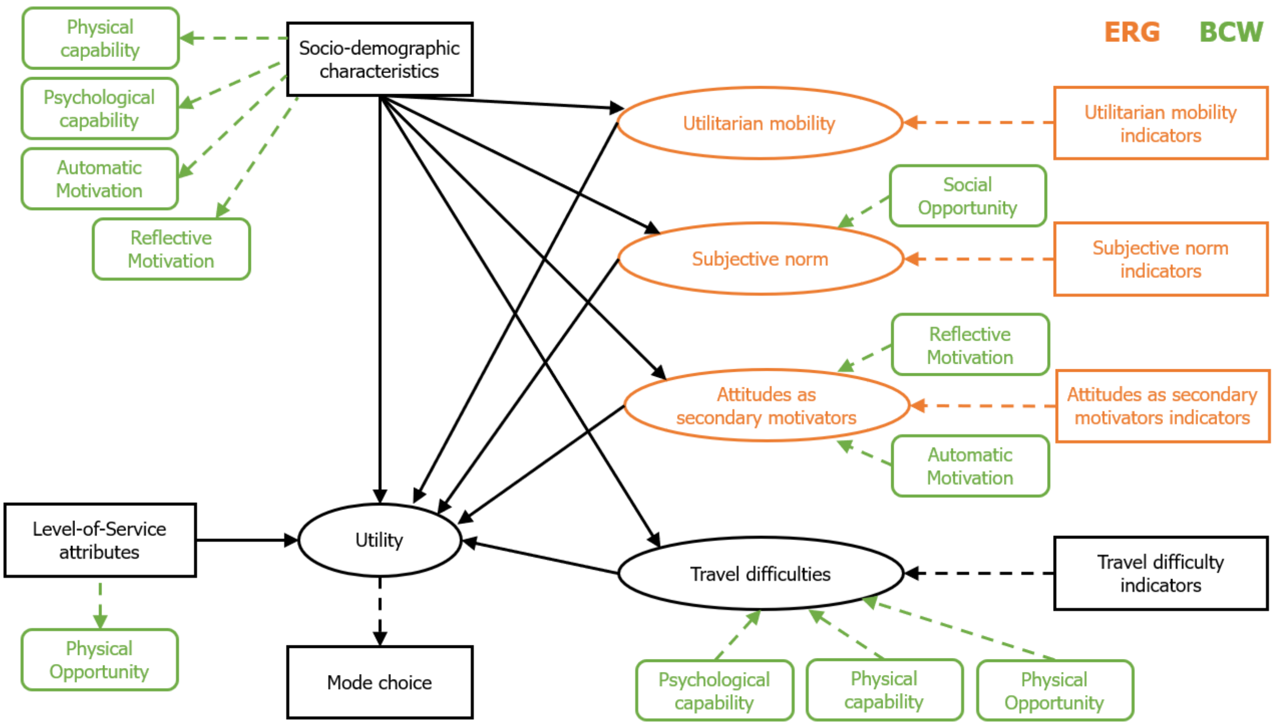


Figure 26: Own interpretation of the link between the ERG theory and BCW theory and the possible impact on mode choice applied on the model framework designed by Bláfoss Ingvardson et al. (2019)

2.6 Intermediate summary of results

E-scooters are very infrequently used in the population compared to e-bikes and conventional bicycles (i.e. 81.5% has never used an e-scooter up to now, while 66.1% has never used an e-bike and 34.4% has never used a conventional bicycle up to now). Also, e-scooters and conventional bicycles are more often used by younger people, while e-bikes are more used by older people (i.e. 50% of the regular e-scooter users, and 38% of the regular conventional bicycle users is younger than 35years old, while 50% of the regular e-bike users is older than 56 years old). This is reflected in the main activity of the regular user, showing that e-bikes are more often used by pensioners, while e-scooters and conventional bicycles are more often used by students and professionally active people.

The use of an e-scooter is higher in Brussels and Liège and is more popular in urban environments. Bicycles and e-bikes are more often used in Flanders, while being popular in urban, suburban, and peripheral environments. In general, e-bikes, e-scooters and conventional bicycles are less frequently used in rural areas, where a higher car use could be observed.

E-scooters are quite frequently used by people with a disability, compared to e-bikes and conventional bicycles (i.e. 30.8% of the regular e-scooter users has some sort of disability, while for e-bikes and conventional bicycles respectively 3.2% and 5.6% has a disability). An e-scooter seems to be a more inclusive transport mode based on this information. Furthermore, regular users of bicycles are the most physically active (both e-bikes as well as conventional bicycles), however, it has to be said that all regular users of these transport modes are more physically active compared to those that are not using them. It is not clear if an increase of physical activity leads to more use of the transport mode, or that the use of the transport mode leads to more physical activity.

A car and conventional bicycle (or even multiple ones) are owned the most out of different transport mode options. Regular users of e-bikes and conventional bicycles are mainly owning them privately, seldomly using shared bicycle schemes. It's possible that the lower supply of shared (electric) bicycles plays a role in this lower use. On the other hand, regular users of e-scooters are owning an e-scooter in 63% of the cases, but shared use is also regularly present. An e-scooter thus seems to have more popularity in terms of shared use compared to bicycles and e-bikes. The availability of shared e-scooters is also indicated to be the highest according to regular e-scooter users compared to bicycles and e-bikes. However, quite some people indicate not knowing if there is a shared device available.

Availability of space to store the transport modes is seldomly an issue at home. At a destination, the storage of e-bikes and conventional bicycles seems to be more often an issue. The larger needed volume of space to store a bicycle, with decent security measures can possibly explain this (risk of theft). Further, a lower income was found for those indicating that storage of these transport modes is more difficult. Storing the transport mode at home is also seen as more difficult for those living in urbanised areas. Lockable bicycle storages can possibly help to solve this issue, but it can also be a signal to provide on-street secured parking for something else than cars. People that are not (frequently) using these transport modes, indicated more often having insufficient space at home or at the main activity to store the transport mode. It is possible that this is a reason for not using it, but can also be a wrong estimation of the needed space, hence not choosing to purchase one of the modes in the first place.

In general, the car remains the most popular transport mode to perform trips, especially for leisure trips. Cycling and walking also have an important share, for all trip purposes. Public transport is mainly used for commuting and in some occasions for leisure. The use of an e-scooter is quite marginal. However, it could be found that regular e-scooter users are less often possessing a driving license (i.e. 28% of the e-scooter riders doesn't hold a license, while for e-bikes and conventional bicycles this comprises 12% to 15%). Since e-scooters are most often used in urban areas, are easier to store, and are used by younger people, it can possibly partially explain the lower driving license possession.

Regular users of conventional bicycles, e-bikes, and e-scooters are less often taking the car compared to those that are not regularly using these transport modes. Reversely, most of this lower car use is compensated by the use of the bicycle, e-bike, or e-scooter itself. Furthermore, regular users of e-scooters and conventional bicycles are more often using public transport compared to non-regular users, while e-bikes are a direct competitor of public transport. For walking no differences could be observed, meaning that walking is not heavily impacted by any of these transport modes. Furthermore, the use of an e-scooter does not impact bicycle use, since regular e-scooter users are still equally often using a bicycle compared to the other non-regular users of the different transport modes. It can be stated for these transport modes, that when one mode is added to the mobility mix (e.g. e-scooter), it doesn't limit a person in options. It just broadens the 'portfolio' of possible modes. The null-effect on walking also tends to contradict previous findings. Caution is needed with regards to the framework of this questionnaire. Here general effects and general use was questioned while other research tends to focus more on specific transport mode replacement on a trip level (e.g. ask for a specific trip which transport mode they otherwise would have taken). Therefor, direct comparisons with these studies cannot be made. However, this more general approach does lower the risk of coincidental transport mode replacement (e.g. took the car because someone needed to pick up errands), while taking deliberate choices more into account.

Trip lengths differ between the transport modes. Walking is quite popular for first or last-mile displacements as well as trips up to 5km (more leisure oriented), while the car and public transport show the highest potential for distances >20km. E-scooters and conventional bicycles show an equally high share in first and last-mile trips, but e-scooters are also very popular for distances between 5-10km, compared to conventional bicycles which are more frequently used for trips between 2-5km. E-bikes also show the highest use with distances between 5-10km, but are additionally very frequently used for longer trips, being a direct competitor of public transport. This tends to show that each transport mode is used for different trip lengths, but a combination of different transport modes can also impact the overall modal split of the user.

The impact of COVID was visible in this questionnaire, showing that walking and cycling gained popularity, while the use of public transport drastically decreased. Also, e-scooters are now a bit more frequently used compared to the pre-covid situation.

The choice for an e-scooter, e-bike, and conventional bicycle depends on multiple factors for which the fulfilment of needs was taken into consideration. For regular e-scooters users, utilitarian aspects, the subjective norm, and higher order attitudes are nearly equally important. However, the view about what others believe or think is more important for them, than it is for cyclists. The desire to belong to, or be a part of, the community thus seems to play a more important role for e-scooter users compared to cyclists. Practical considerations and higher order needs are less important for regular e-scooter users, compared to regular bicycle users, probably since the e-scooter doesn't lend itself towards these aspects (i.e. the e-scooter is less practical, for example when transporting goods). This difference with conventional bicycles and e-bikes can possibly be explained by the lack of knowledge and lack of market maturity of e-scooters impacting the attitude, or seeing this transport mode in a broader picture to not only fulfil a specific type of need.

For bicycle use (both electric as well as conventional), the opinion of others doesn't lead to specific use of the transport mode. However, utilitarian aspects and higher order needs are very important. For regular e-bike users, utilitarian aspects are even more important than for regular users of conventional bicycles. A real focus is laid on the practicality of an e-bike (e.g. going to work, doing groceries, running errands, meeting friends, etc.), as well as the greater good (e.g. since it is good for the environment, since it improves the situation in cities, since it gives a good feeling, etc.). Regular users of conventional bicycles primarily focus on the greater good, while rating the practicality lower. This difference with an e-bike is probably present due to the motorised support of an e-bike, making it possibly a better alternative to the car in terms of practicality.

Subsequently, different underlying factors can be the reason for which people are not using any of these transport modes. They mainly refrain from using them because of motivational reasons (both automatic and reflective), as well as the physical opportunity, physical capability, and psychological capability. This means that an e-bike, e-scooter, and conventional bicycle are often not taken because:

- people do not enjoy taking it;
- people do not automatically think of these options as an alternative;
- people do not take the time to see if it fits their needs;
- people do not have sufficient means (i.e. time and money) to use it;
- people do not have it physically available (e.g. no private mode, but no shared modes available either);
- people do not have facilities available (e.g. showers, storage place, etc.);
- people have physical constraints in terms of strength, and physical endurance;
- people lack skills to use it;
- people have not enough confidence in the transport mode;
- people lack knowledge;
- people have mental constraints making it difficult to fully concentrate.

The social opportunity is playing a minor role (e.g. more support from others, having others around you that do it as well, etc.), which is also seen with the needs (i.e. subjective norm was already found to play a smaller role).

It was found that people with a disability have more problems in relation to the physical and psychological capability (i.e. a direct effect of the disability), as well as physical and social opportunity (i.e. more time, money, and accessibility constraints, while also taking more into account what others might think of them). Further research is advised for this.

While for each transport mode certain hindering factors are more important than others, especially conventional bicycles seem to suffer more from the impeding factors. While for some factors, differences were absent between the transport modes, the use of a conventional bicycle was more impeded in terms of automatic motivation, and physical capability. The latter is not surprising, due to the lack of power support, compared to the other transport modes. Since cycling with a conventional bicycle requires much more physical effort compared to using an e-scooter, and to some extent e-bikes (when the length of the trip is ignored), it is quite logical that this is seen as a limiting factor. In fact, the physical capability is even more hindering compared to the physical opportunity for taking a bicycle, that originally was seen as a more hindering factor over all transport modes. To add, a correlation was made with physical activity performed by the respondent on a weekly basis, showing that more physical activity resulted in less impact of this physical capability. However, measures to increase the use of the transport modes do not have to be tailored to a specific transport mode, since all transport modes can benefit from the same actions. In general focus can be laid on interventions targeted towards motivation, capability, and physical opportunity to make people ready for the use of these transport modes. Focus on the social opportunity is not necessarily needed. If cycling wants to be more promoted however, more focus can be laid on the aspects of physical capability and automatic motivation.

So, while the higher order and lowest order needs are seen as the most important factors to choose the transport modes, it is actually the capability and motivation that stands non-regular users in the way of using it. This seems to confirm that, overall, regular users are being more in favour compared to non-regular users, mainly as a result from trying the transport mode and therefore acknowledging the positive aspects. However, the physical opportunity cannot be ignored. This physical opportunity can lie out of the control of the individual itself (i.e. a person cannot easily find more time, more money, have more modes available, etc.) or can be a result of a wrong perception (i.e.. thinking that the transport mode is slower, more expensive, not readily available, etc.) . The subjective norm and social opportunity seem to have the lowest influence.

Correlating all this information on behaviour with the mobility characteristics and previously mentioned findings (e.g. storage possibilities, usage among disabled people, the amplifying effect of choosing public transport on bicycles and e-scooters, the degree of urbanisation, age of the users, etc.) shows that e-scooters, e-bikes, and conventional bicycles have their own specific field of use not just replacing another mode of transport. Further, it has to be mentioned that a person who is using an e-scooter, isn't going to choose a bicycle if the e-scooter would be taken away (visible in the non-use figures that just mainly showed higher car use). The same can be said about conventional bicycles and e-bikes, showing specific reasons for taking the specific transport mode.

Nevertheless, it is possible that e-scooters, e-bikes, and bicycles can be rivals of each other for specific trips (e.g. an e-scooter is equally often used as a bicycle for first-last mile trips), but the collective effect on the replacement of car trips, seems to be a more beneficial effect. It further shows that mode choice is a difficult to grasp concept, not solely leaning on derived demand anymore, but taking much more aspects into consideration. This was made clearly visible by the psychological models, and the simple fact that a conventional bicycle is very frequently owned in the household, even by people that can be considered as non-regular users (i.e. those riding less often than on a weekly basis). Showing that just the fact of having access to a mode doesn't mean that it makes the person a regular user.

3 The environmental impact of e-scooters

3.1 Methodology

The environmental performance, with respect to CO_2 emissions, of e-scooters is assessed in this section. The assessment follows the steps as presented in the ISO 14044 standard for life cycle assessment (LCA). The goal of this part of the study is multi-facetted. The first goal consists of evaluating the impact on the environment of different stages of the life cycle of e-scooters, with a differentiation between shared and private e-scooters. Secondly, the goal is to understand if and to which extent e-scooters are having more impact than the transport modes it replaces. Finally, improvements are discussed and the expected evolution is evaluated.

The scope of the study can be summarised in the following system boundaries diagram (Figure 27). For the calculations of the impact of the materials and components on the environment (CO_2 equivalents) the entire list of materials is used, which will be discussed further on. In the upcoming section only the main components are discussed.

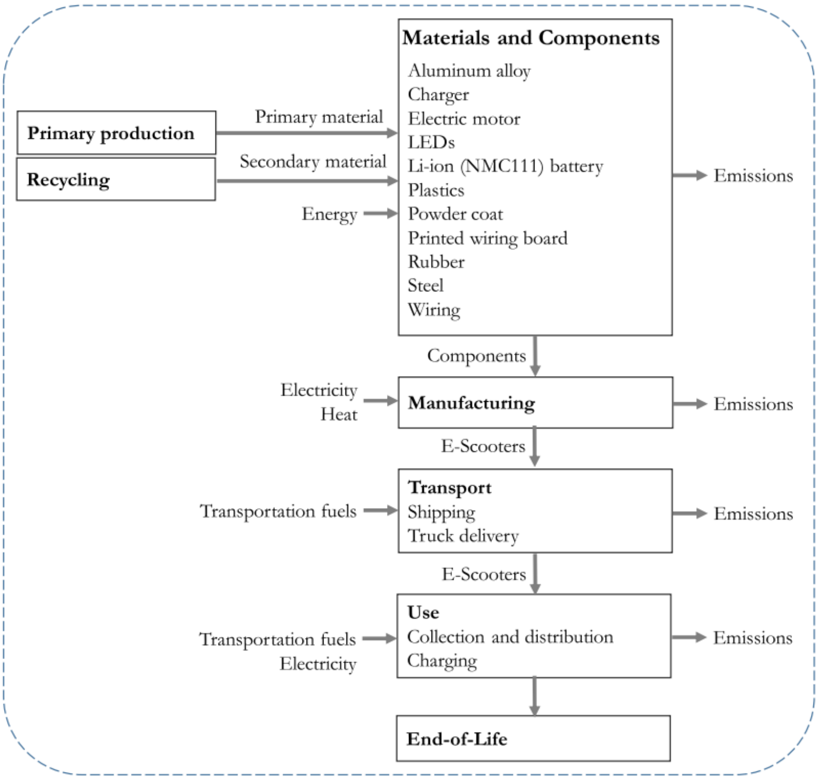


Figure 27: System boundaries diagram. Source: (Hollingsworth et al., 2019).

The main information used for this study is based on a report (Cazzola & Crist, 2020) by the International Transport Forum (ITF). Additionally, an assessment tool developed by ITF, available to the general public, was also used in order to quantify the environmental impact of different transport modes. The tool was **adapted to the Belgian situation**, in which some of the numbers where updated in relation to transport in Belgium (i.e. originally USA data), as well as the Belgian electricity mix instead of the global average. By doing so, since these figures differ quite a bit, the analysis is more up to date and applicable to e-scooters in Belgium.

Secondly, a thorough literature review was conducted to identify existing LCAs of e-scooters. From the selection of papers, a broad range of estimates were obtained of the life cycle greenhouse gas emissions of shared and private e-scooters in a number of different scenarios.

Lastly, to complement the information available in the scientific and grey literature and to include the latest insights, interviews were conducted with e-scooter sharing providers Bird, Lime, Voi, Dott, and Tier, as well as an interview with a private e-scooter retailer. Based on prior knowledge from the literature review, these interviews tackled a number of different topics:

- The production of the required materials is the most polluting phase of the life cycle
  - Which components break most often and how the providers plan to extend the lifetime
  - How the lifetime of an e-scooter has evolved
  - How the end-of-life of an e-scooter is determined and if a maintenance policy is in place
  - Further details about the end-of-life, such as what happens with the battery and the e-scooter itself when they reach the respective ends of their life cycle.
- Operational services make up the second most polluting aspect of the life cycle
  - The distribution and charging process and the impact of swappable batteries
- Ambitions regarding sustainability and the expected timeframe to achieve these ambitions

From now on, in this report, a reference to the providers is made anonymously if that information was gathered during an interview. Elements highlighted during these interviews are included in the discussion of the LCA whenever relevant. The providers may be named when the information is openly available to the general public.

3.2 Life cycle inventory

In this section all the factors that possibly contribute to life cycle greenhouse gas emissions of an e-scooter are identified. The factors can be grouped into five large components, which are shown in figure 28. For each factor within a component a number of scenarios are discussed. To get a view on which of these theoretic scenarios are put into practice at this point in Belgium, information gained from the interviews with e-scooter sharing providers is included.

Additionally, to focus our efforts on the current situation in Belgium, the details are filled in for e-scooter sharing services in Brussels if adequate data is available. If such data is not available, data from elsewhere in the world, if applicable, is used instead. In the first place Brussels is chosen because it has the highest concentration of providers, the highest number of available devices, while being the only reference city from Belgium used in international comparisons. Prudence is thus needed to transpose the discussion and conclusions to other cities in Belgium. While the transport for the initial delivery, the operational services and infrastructure can differ from city to city, the other components and general ideas remain the same.

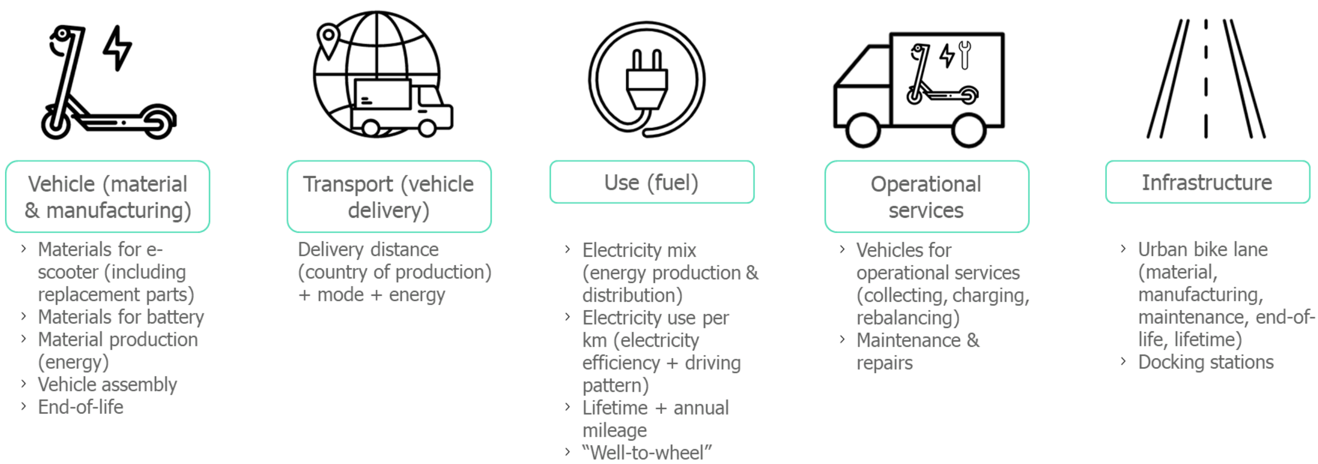


Figure 28: The components contributing to life cycle GHG emissions of a shared e-scooter.

3.2.1 Vehicle

The vehicle component contributes to the greenhouse gas (GHG) emissions through the production and assembly of the required materials. It is therefore needed to identify the major components of micromobility vehicles, and the factors that define the lifetime. Based on figure 29 a list of the most important components can be derived:

- The frame
- The battery
- The electric motor
- The motor controller
- The usage parts (tires, brakes, rims, suspension)
- The electronic components

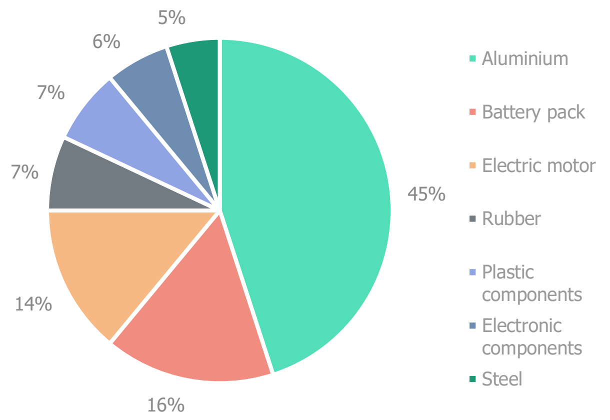


Figure 29: Share of materials of an e-scooter. Source: (Severengiz et al., 2020)

Other aspects such as the design, production, and end-of-life are also tackled in this section since they have an impact on the life cycle emissions of e-scooters and can thus be seen as part of the vehicle component.

Note, that large quality differences can be present on the market between private e-scooters. Electric "toy like" kick scooters, with a cost of 100-200 euro, differ largely with 'street-worthy' vehicles with a cost usually above 500 euro. This difference can have a big impact on the vehicle's life cycle and its life cycle emissions. This study could not elaborate on this difference in this section.

3.2.1.1 Frame

Based on market research, most of the shared and private e-scooter frames are currently made out of aerospace or industrial-grade aluminium alloy, due to their lightweight characteristics, stiffness and corrosion resistance, making them suitable for tough use conditions. About half of the total weight of an e-scooter comes from the aluminium used for the frame which is made, for a certain part, out of recycled aluminium. The frame of the latest e-scooter of Bolt, the operator with the largest market share in Europe, is made entirely of recycled aluminium (Bolt Blog, 2020). Hence, an important change was made to start using recycled aluminium for the frame which makes the most recent generations of shared e-scooters and e-bikes more sustainable. Parts of the chassis that need to be reinforced can be composed out of steel, but this increases the weight of the vehicle. Higher-end vehicles (mostly privates ones) can consist out of carbon fibre parts as it is lighter and sturdier than aluminium. On the other hand is it more expensive and more difficult to use during the manufacturing process. The share of recycled aluminium in private e-scooters could not be determined and is therefore estimated to be low.

3.2.1.2 Battery

The battery of a micromobility vehicle stores and provides the energy to the electric motor in order to propel the user forward. The battery capacity, expressed in Wh or Ah, defines the range of the vehicle. After a brief private market consultation, most e-scooter batteries proclaim a battery capacity between 4Ah up to approximately 15.3Ah which translates into a range between 12km and 64km.

Different technologies of rechargeable batteries exist such as Li-ion, Lead-acid, Ni-Cd , etc. Based on market research of most recent private and shared e-scooters, Li-ion is the most used battery type due to its intrinsic properties (Clean Energy Institute, 2020):

- High energy efficiency and power density
- High reliability and low maintenance
- Reasonable self-discharge rate
- A great lifespan with a high number of charging cycles

To ensure the safety of the battery during its utilization and charging process, the battery should be well-produced, insulated and equipped with a Battery Management System (BMS) that monitors its State of Health (SoH) (Bird Cities Blog, 2022). The BMS preserves the lifetime of the battery by monitoring temperatures, voltage, and current during usage of the battery. It also determines the battery charge level, arranges the recharge, and prevents the battery from being completely overcharged or too deeply discharged (Vezzini, 2014). Furthermore, the BMS helps to detect abnormalities, which can jeopardize the lifetime of the battery. These can be a short-circuit or water intrusion, which results in disabling the battery, or an increased battery temperature, for which the voltage and current will be adjusted to avoid pushing the battery beyond its operating conditions (Jossen et al., 1999). The BMS can thus play a large role in the optimisation of the battery, its total lifetime, and the life cycle of the device.

In practice, two main battery mounting types are used in micromobility vehicles: batteries embedded in the frame and swappable batteries. Each type has their own benefits and drawbacks. While shared vehicle operators adopt both types of mounting on their e-scooters, private e-scooters are generally equipped with an embedded battery. Embedded batteries are less prone to theft and damage, since they have reinforced enclosures and less chance to be mishandled during charging (Battery Solutions, 2022). A drawback of this technology is the charging process that requires to take the whole vehicle and thus increases the burden of the operation. From a financial point of view, the use of swappable batteries decreases recharging costs by 60-80%, thus making them essential in order for shared e-scooter providers to be profitable (The Next Web, 2022).

For those reasons, swappable batteries seem to have convinced operators, since the latest models from Bird, Lime, Voi, Bolt, Dott and TIER are equipped with them. Swappable batteries are seen as a technology that can tackle the issue of the environmental impact and durability of shared micromobility vehicles. According to LCAs performed by third-parties for some operators, it could reduce operational CO_2 emissions by 56% to 81%, but could provide other benefits as well (Dott Blog, 2021). For example, a swappable battery can extend the vehicle lifetime due to the avoidance of wear and tear when being transported or charged in a van. In (Dott, 2022), Dott mentions that 83% of their rides were done with swappable batteries and that it is one of their goals to equip all of their vehicles with swappable batteries by 2025.

However, drawbacks can arise for both private and shared vehicles when batteries are swapped. Firstly, a bigger risk for damage arises since more moving parts are in play, the battery can be dropped, or can be improperly placed. This can compromise the safety of the staff or the user and can jeopardize battery lifetime (Gauquelin, 2020). Secondly, this type of battery is generally heavier and bulkier and the frame needs extra reinforcements, a lock and a connector which makes the vehicle heavier, which can also be seen as an advantage with shared devices (Lawrence, 2021). Lastly, vandalism also plays a big role. Swappable batteries need to have reinforced enclosures and measures in place in order to avoid easy theft, but on the other hand this can also make it more difficult for the operator to swap the battery itself.

3.2.1.3 Electric motor

The electric motor largely determines how an e-scooter performs. A market review shows that the motor can be located at the front or rear wheel with the brushless electric motor as the most used type of motor. The advantages of using this brushless technology are the following (Horizon Micromobility, 2022):

- High efficiency
- Reduced size
- Long lifespan
- Silent
- No brushes wearing out (less maintenance)

A small but strong motor that lasts a long time and requires little maintenance is ideal from the standpoint of minimizing the emissions associated to manufacturing and maintaining it.

The electric motor is mainly defined by one feature, its power expressed in Watt, which defines the acceleration capabilities, the ability to carry heavy loads and climb hills. In the specification sheets of manufacturers, two types of power can be derived, namely peak power and continuous/rated power. The first one refers to the maximum power that the electric motor can deliver in a short period of time, while the second refers to the power that the electric motor can supply continuously. Therefore, it is more appropriate to use the latter when comparing different motor technologies, as it is more representative of its real use. Based on a market research, the continuous power of electric motors that can be found on homologated e-scooters ranges from 250W to 500W.

3.2.1.4 Motor controller

The motor controller makes the link between the battery and the electric motor and receives control signals when the driver uses the throttle or brakes. During an interview with a private micromobility seller, it was indicated that this component is quite sensitive and that it is a recurring reason for e-scooter repairs, especially for cheaper models, but that it is not expensive to repair if a controller is still readily available on the market.

3.2.1.5 Usage parts: tires, brakes and suspension

Three types of tires exist, each with their own advantages and disadvantages (Strobel, 2021):

Table 7: Different types of tires mounted on e-scooters.

Type	Pneumatic 	Solid 	Honeycomb 
Benefits	• Good grip • Good shock absorption • Easy to find	• Puncture resistant • Little maintenance	• Puncture resistant • Softer than a solid tire
Drawbacks	• Maintenance (chance of punctures)	• Heavier • Bumpier ride • Loss of traction	• Expensive

Based on a market research on e-scooters, pneumatic and solid tires are the most popular, both for private and shared e-scooters. Solid and honeycomb tires are used on some shared e-scooters due to their puncture resistance and fewer maintenance, which is more convenient for intensive use. The heavier solid tires thus contribute to the higher weight of shared e-scooters compared to private e-scooters with pneumatic tires.

The market research further shows that micromobility vehicles can also have a suspension that helps to dampen the vibrations when riding on bumpy roads. Most inexpensive e-scooters do not have suspensions while more expensive e-scooters have hydraulic, rubber or spring suspensions. The latest models of shared e-scooters are equipped with a suspension system for solid or honeycomb tires whereas e-scooters with pneumatic tires do not have a suspension system.

Different types of brakes exist with two main categories to be distinguished: mechanical brakes composed of drum or disc brakes, and electronic brakes. Their characteristics are summarized in table 8 (Electric Scooter Guide, 2022a).

Table 8: Different types of brakes on e-scooters.

Type	Benefits	Drawbacks
Disc 	• Excellent braking power and control • Performs well in wet conditions	• Maintenance • Can cause damage to wheel rotor

Drum 	• Low maintenance • Consistent performance in wet conditions	• Difficult to repair • Heavier • Lower performance than disc
Regenerative 	• No added maintenance • Energy recovery	• Poor braking performance
Electronic 	• No added maintenance	• Poor braking performance
Foot brake 	• No maintenance • Simple design	• Poor performance (especially in wet conditions)

Market research shows that shared e-scooters are more likely equipped with drum brakes, probably for their low maintenance while private scooters mainly have disc brakes. The heavier drum brakes thus contribute more to the mass and life cycle impact of shared e-scooters compared to private ones.

Regenerative braking is not interesting for e-scooters in terms of energy recovery compared to electric cars. Since braking happens quite shortly and the vehicle has a low speed and mass, little kinetic energy is recovered. It is assumed that the energy recovery due to regenerative braking, under certain conditions, could increase the range of the battery with as little as 2% and is therefore not interesting in view of a LCA (Electric Scooter Guide, 2022b).

3.2.1.6 Electronic components

Electronic components are vital for the safe and proper use of micromobility vehicles. The software and hardware developed for the latest generations of vehicles offer more advanced features. Thanks to high-tech sensors, IoT products (Internet of Things) and real-time connectivity, it becomes possible to address safety issues, increase the lifetime of the vehicles and improve user retention.

For example, e-scooters can be equipped with IoT sensors that allow the provider to remotely diagnose battery levels, damage and the overall condition of the e-scooter (Ericsson, 2021). In this way, predictive maintenance, where an operator repairs or replaces a component before it breaks, becomes possible. These innovations lead to more efficient operational services by not wasting time and resources driving to collect e-scooters that do not yet require charging or maintenance. Other examples of sensors that improve the user experience include a geographical location sensor, used to provide the exact location of the e-scooters, and a near field communication (NFC) sensor that enables online payments and contactless unlocking of the e-scooter.

As a result the initial investments in the materials for the electric components are well worth it to achieve a longer life cycle and more efficient servicing of the vehicle.

3.2.1.7 Vehicle and battery manufacturing, assembly and disposal

The energy consumption of the vehicle and battery manufacturing, assembly and disposal of shared e-scooters is summarized in the figures below. The numbers are taken from the assessment tool used for the LCA in (Cazzola & Crist, 2020).

Figure 30 shows that the majority of the energy consumption is due to manufacturing of the required materials and stresses the importance of less energy demanding processes. Using an alternative low carbon method to melt the aluminium reduces the manufacturing energy consumption by 27% and 25% for the first and new generation of e-scooters respectively. The new generation e-scooters require more energy to be manufactured than the first generation e-scooters due to their higher weight (25 kg vs 11 kg) and larger battery (0.55 kWh vs 0.33 kWh). Similar observations can be made with regard to the manufacturing, assembly and disposal of the battery as shown in figure 31. In this battery production, the use of low carbon aluminium smelting is less impactful since for lithium-ion batteries only the housing is made of aluminium, compared to large parts of the e-scooter.

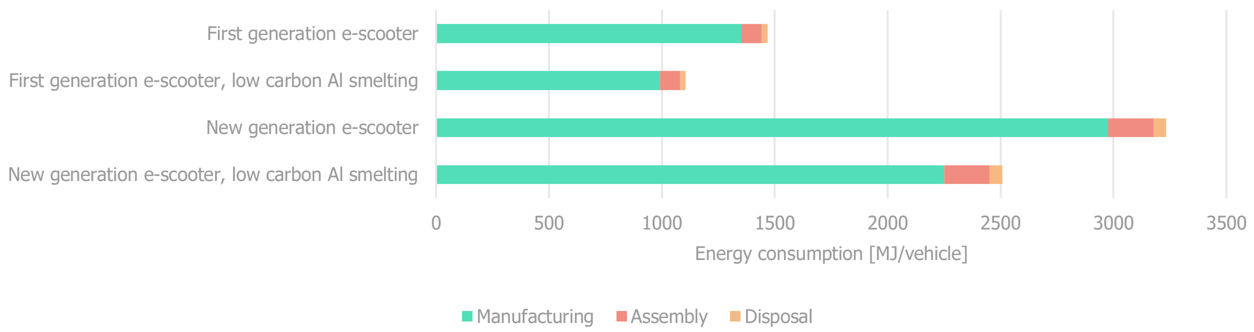


Figure 30: Energy consumption for vehicle manufacturing, assembly and disposal

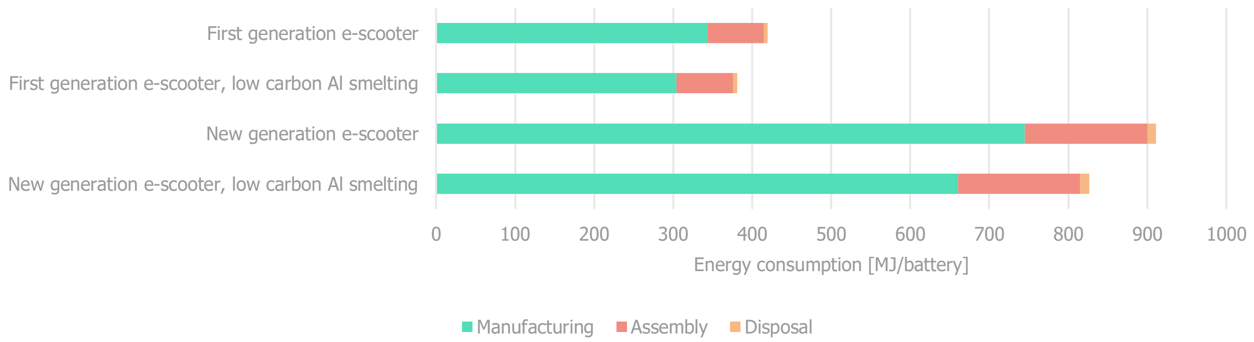


Figure 31: Energy consumption for battery manufacturing, assembly and disposal

3.2.1.8 Vehicle design

The design of micromobility vehicles has evolved over the last years. Especially the shared e-scooters have experienced a big evolution aiming at increasing vehicle lifetime. The first generations of shared electric scooters were models that were made for private use and sourced from private companies, such as Xiaomi and Segway-Ninebot, and therefore not designed for frequent use, abuse, or harsh weather conditions (The Verge, 2019). As a result, the first generations of shared e-scooters had a limited lifespan, as short as 3 to 4 months, and the environmental impacts related to the production of the e-scooter were therefore poorly amortised (Schuller & Aboukrat, 2019). The latest generations of e-scooters on the shared market show a promising evolution in design, making them increasingly suitable for shared and intensive usage (which will be further discussed in section 3.3).

An important change that operators and manufacturers highlight concerns the fact that their latest generation of electric scooters have an increasingly circular design, including modularity, which allows to extend the vehicles' lifetime (Lime, 2019). A modular design means that the vehicle is designed with the idea of easily swapping/replacing vehicle components in order to use a device for a longer time before being thrown away or recycled. Based on the feedback from past experiences, which came to light during interviews with shared mobility operators, operators are able to identify which vehicle parts are the most susceptible to break, therefore changing the design of the part accordingly to replace it more easily on the vehicle. This modularity can also be found in the hardware of the latest generation of Voi vehicles, where extra slots for sensors have been intentionally left open, so that a new feature can be added without the need to produce an entire new vehicle (Voi Blog, 2021). These innovations help mitigate the initial impact of vehicle manufacturing.

3.2.1.9 End-of-life

It should be noted that the market is not yet mature enough to fully evaluate the end of life of e-scooters right now. What is certain is that one of the main determinants for the end-of-life of an e-scooter is the state of the battery. After all, an e-scooter with a battery that reached its end-of-life can no longer store adequate charge to have a long range, which makes the device quite useless. When the battery reaches this point, the choice emerges to buy a new battery or a new e-scooter altogether. A private e-scooter retailer indicates that the latter choice is more popular for private e-scooters, given the interest of clients in new features on newer e-scooters. Therefore extending the battery lifetime is of crucial importance. However, a disposed e-scooter is not thrown away. The functional usage parts which are prone to breaking, such as tires, brakes and the motor controller can be reused. By doing so the GHG emissions released for manufacturing a new set of components are avoided, while the lifetimes of the existing components are extended.

Alternatively, the battery may be replaced and the disposed battery can be given a second life and serve a purpose in a different vehicle, such as powering a wheelchair, as indicated in the interviews with e-scooter sharing providers. In recent events, decommissioned e-scooter batteries are being used as powerbanks for journalists on the ground in Ukraine (Klimt, 2022). In Belgium Bebat also collects and recycles batteries.

In their first sustainability report, (Dott, 2022) the shared e-scooter provider Dott mentions that monthly 1.4% of their vehicles are broken beyond repair. Additionally 95% of damages are repaired and 90% of parts of unusable vehicles are reused. The same company exports e-scooters that require more frequent maintenance to Poland (Romain, 2022), where labour costs are lower. In this way the lifetime of these e-scooters is extended when these devices are being used again in the cities of Poland.

3.2.2 Transport

The transport concerns the initial delivery of the vehicle from the place of manufacturing to the customer. Different studies, together with the interviews with micromobility operators and providers, confirm that most well-known e-scooters (e.g. Xiaomi, Segway-Ninebot) are produced in Asia, particularly in Shenzen, China.

To deliver the e-scooters to Europe, a combination of transport by ship and truck is commonly used. The characteristics of the transport in a study on shared e-scooters in Brussels, Belgium (Moreau et al., 2020) are summarized in the table below. It concerns freight shipping from Shenzen, China to Rotterdam, The Netherlands followed by a truck drive to Brussels. The largest part of the trip is done by the most energy efficient mode of transport, which is beneficial to minimizing the corresponding GHG emissions. Alternatively, the shipping can be substituted by a trip of 11000 km by freight train, which consumes a similar amount of energy per vehicle.

	Delivery distance [km]	Energy consumption [MJ/vehicle]
Ship	20642	29,7
Truck	152	3,3

3.2.3 Use

The use component concerns the GHG emissions in the part of the energy chain which is commonly referred to as "Well-to-Wheel". This part can be further subdivided into "Well-to-Tank" and "Tank-to-Wheel". The GHG emissions in the Well-to-Tank phase depend on the electricity mix and the CO_2 emissions associated to the production and distribution of each source of electricity.

Different scenarios regarding the electricity mix exist, ranging from only using durable energy sources to using exclusively coal. The share of each source of energy in the global and Belgian electricity mixes of 2020 is shown in table 9. These numbers are more recent than the ones used in (Cazzola & Crist, 2020).

Table 9: The global and Belgian electricity mixes in 2020. Sources: (World Energy Data, 2022) and (IEA, 2022).

	Share in global electricity mix	Share in Belgian electricity mix
Oil	2.8%	0.1%
Natural gas	23.4%	29.8%
Coal	35.1%	2.1%
Nuclear power	10.1%	38.7%
Biomass and other	3.5%	7.7%
Renewables	25.1%	21.6%

Note that e-scooters do not have emission pipes. Therefore there are no CO_2 emissions coming from transferring the energy from the tank or battery to the wheels. Hence the Tank-to-Wheel phase is only influenced by the lifetime mileage and the efficiency of the e-scooter, i.e. the amount of electricity used per km travelled.

During our interviews with e-scooter sharing providers and manufacturers it came to light that the market is not yet mature enough to estimate the exact lifetime of e-scooters. Operators have increased the lifetime of their e-scooters from generation to generation. Estimates vary from 6 months for early generations to 5 years for the latest models of shared e-scooters. One provider mentioned that about half of their first generation e-scooters are still operational after 36 months while the lifetime was initially estimated at only 18 months. The lifetime of a private e-scooter is highly subject to personal use and very little is known about it. This large uncertainty will be one of the responsible factors for the large variance in the estimates of the life cycle impact of the vehicle.

It should be noted that the main determinant of the end of life of e-scooters is through the battery reaching the end of its life rather than secondary influences such as vandalism. Providers have indicated that severe vandalism is rare. Therefore the total number of kilometres travelled and number of battery cycles more accurately reflect the lifespan of the vehicle rather than years of ownership. Hence mileage of the vehicle is another important factor in determining life cycle impact.

The lifetimes and mileages of the private and shared e-scooters discussed in this report are summarized in table 10. The estimates of the private and first generation shared e-scooter are based on, but are not entirely the same as in the ITF report, who in turn relied on the scientific literature and their personal communications with operators. The chosen lifetime mileage for the first generation e-scooter of 18 months differs from the estimate of 10 months used in the ITF report. The early estimates in the scientific literature turned out to be rather pessimistic. Based on our interviews with shared e-scooter providers, the scientific literature and the sustainability report (Dott, 2022), we arrived at the estimated lifetime of 18 months for the first generation e-scooter and the estimate of 36 months for the newest generation e-scooter, shown in Table 10.

Despite our best efforts to acquire accurate estimates of e-scooter lifetimes and lifetime mileages through personal communication with shared e-scooter providers, no precise estimates were given. Given that multiple providers claimed that their first generation e-scooters had an expected lifetime of 18 months, but were still operational after 36 months, they may have been overconfident in their estimates of their latest generations lifetime at 60 months. Therefore, with technology improving, it seems reasonable to assume a lifetime of 36 months. With ridership and fleet size increasing steadily up 76% and 15% respectively, in the second quarter of 2022 compared to 2021, and a 177% increase in the number of trips year-on-year (POLIS Network, 2022) a daily mileage of 10 km seems like a reasonable, conservative estimate.

Table 10: E-scooter estimated lifetimes and mileages.

	Vehicle lifetime [months]	Mileage [km/year]
Private e-scooter	36	2200
Shared e-scooter (first generation)	18	2900
Shared e-scooter (newest generation)	36	3650

3.2.4 Operational services

The operational services component concerns the GHG emissions associated to the collection and redistribution of shared e-scooters for charging and maintenance. This component is not applicable to private e-scooters. The environmental impact of maintaining an operational fleet of shared e-scooters is mainly influenced by the mode of transport for collection of the swappable batteries or the entire e-scooters, and the distances to cover. For each influencing factor, a number of scenarios can be considered.

For the collection of the e-scooters or their batteries, an electric van could be used instead of a regular combustion van. In the scenario of swappable batteries, e-scooter sharing providers are exploring the option of less polluting service vehicles even further by manufacturing dedicated electric cargo bikes that can carry batteries. The latest launch of a fleet of 2000 shared e-scooters by TIER Mobility in Brussels puts these alternatives into practice (Intelligent Transport, 2022). Dott uses electric vans as well as cargo bikes to carry out the field operations in Brussels. 55% of their global operation fleet is made up of electric vans and cargo bikes, with a goal set to reach 100% by 2025, as stated in (Dott, 2022).

Some of the providers use outsourcing to carry out field operations. In some cases, their contracts include a supplement fee for ensuring the green energy or equivalent compensation. However, it is not possible to estimate to which extent the contractors follow the agreement and how the operations are executed. Especially in the past, a lot of evidence was circulating which demonstrated poor environmental performance (Carpenter, 2019; Conti, 2019; Hendrickx, 2019; Tire meets road, 2018). Maintaining the operations in-house require sufficient fleet size and business structure that allows field operations to be fully carried out according to standards preached by the providers. On the other hand, external contractors could be enlisted to collect batteries/scooters from different brands, which could - at least theoretically - be more efficient than when every e-scooter provider needs to cover the entire city in which several operators are present either way. Alternatively, providers could also enlist the help of their consumers by attaching rewards, such as a free ride, to the act of taking an e-scooter away from a cluttered street.

Changes in service policy can also improve the service efficiency, in particular if the e-scooters have swappable batteries. For example, collecting exclusively the batteries instead of the entire e-scooter allows for more e-scooters to be serviced by a single service vehicle. Collecting and replacing the empty batteries on site can further decrease the ratio of service-km to e-scooter-km.

Finally, servicing distances can be lowered by increasing the density of designated parking areas or through the use of docking stations, which can especially be done in urban areas of large cities. In this way, the service vehicles do not have to travel as far in between and can take more efficient routes (for docking stations specifically further discussed in section 3.2.5). By enforcing a policy that requires users to park the e-scooters in these designated areas the operators have to make less stops. From market research it appears that most providers have such a policy in place. Some policies require users to take a picture of the parked e-scooter, in order to ensure that the parked e-scooter does not hinder pedestrians, obstruct emergency vehicles passages or disturb other road users.

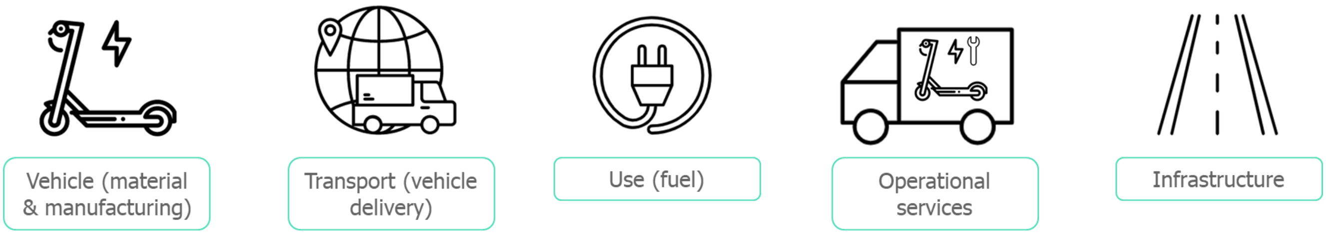
3.2.5 Infrastructure

The infrastructure component concerns the GHG emissions associated to the construction, maintenance and end-of-life management of specific infrastructure required for vehicle operations. This component is applicable to both private and shared e-scooters, with shared e-scooters possibly requiring docking stations, though they are typically dockless. Docking stations that also charge the e-scooters, often wirelessly, exist as shown in figure 32 and have also been introduced in Belgium (e.g. Corda Campus Hasselt, Terhills in Maasmechelen & Dilsen-Stokkem). The addition of such charging stations could eliminate part of the operational services, as there would no longer be any need to collect the e-scooters or their batteries for charging. Infrastructure requirements common to both private and shared e-scooters include urban roads and bike lanes. It is assumed that the infrastructure lasts 30 years, far longer than the lifetime of e-scooters and that its status is unaffected by the intensity of usage. Hence the infrastructure component gives rise to a fixed contribution with no influencing factors or different scenarios to be considered, which is why it is often left out of LCAs. Additionally, existing road infrastructure can be used by future e-scooters without further investment (e.g. e-scooter can make use of existing bike lanes)

Figure 32: A designated parking area in Antwerp and a charging station in Atlanta, Georgia. Source: Google Images.

3.3 Environmental Impact Assessment

To assess the impact on the environment of each component of the previous section, we look at the global warming potential through greenhouse gas emissions. Instead of considering each greenhouse gas separately, we evaluate the impacts in grams of CO_2 equivalents per vehicle. After dividing by the lifetime mileage we obtain an expression in grams of CO_2 equivalents per vehicle-km, denoted g CO_2 eq / vkm, which is the measuring unit of our study.



3.3.1 Vehicle

The CO_2 emissions of the vehicle and battery manufacturing, assembly and disposal of shared e-scooters are summarized in this section. This component includes the CO_2 emissions from mining and producing the materials. The numbers are taken from (ITF assessment tool, 2020).

3.3.1.1 Vehicle and battery manufacturing, assembly and disposal

We assume a lifetime mileage of 6600 and 2417 km for the first generation private and shared e-scooters respectively and 5703 km for the newest generation of shared e-scooters. The total CO_2 emissions of the vehicle and battery manufacturing, assembly and disposal in different scenarios are summarized in figure 33 below.

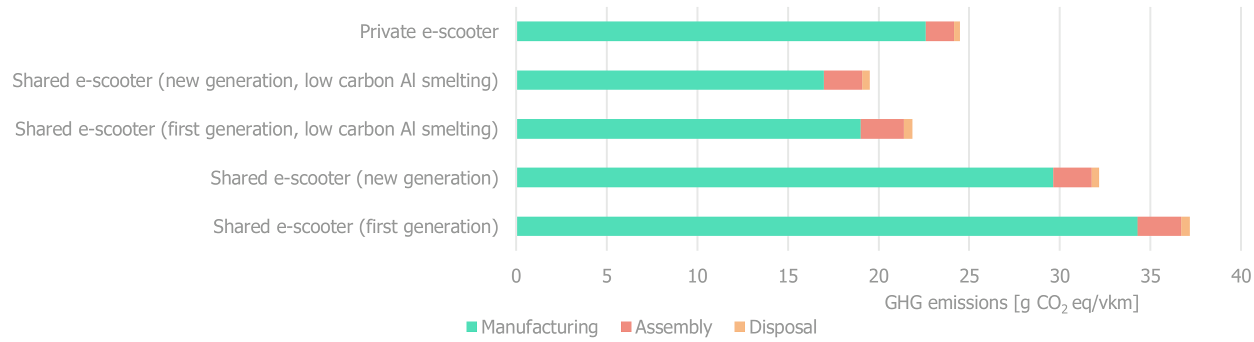


Figure 33: GHG emissions of vehicle and battery manufacturing, assembly and disposal [g CO_2 eq/vkm].

The new generation of shared e-scooters has a lower emission per vehicle-km than the first generation, despite being heavier and requiring more energy for manufacturing per vehicle. This decrease in emissions per vehicle-km is due to the extended lifetime and lifetime mileage.

3.3.2 Transport

The CO_2 emissions for delivery of a single vehicle are summarized in the table below. The table shows how using a more durable mode of transport, such as an electric truck instead of a regular combustion truck, can decrease the CO_2 emissions for that part of the delivery by 33%. However, since the trucking only makes up a tiny part of the total trip the difference is insignificant. When larger parts of the journey need to be done by truck – for example for the transport to countries without close access to ports – the environmental gains of electric trucking compared to regular trucking are more pronounced.

It should also be noted that the total CO_2 emissions for delivery are relatively small compared to the CO_2 emissions in the other sections.

	Delivery distance [km]	GHG emissions for delivery [g CO_2 eq/vehicle]
Ship	20642	2763
Truck	152	298
Electric truck	152	199

Dividing by the assumed lifetime mileages of 6600 and 4350 km for private and shared e-scooters respectively gives the following emissions per vehicle-km.

	GHG emissions for delivery [g CO_2 eq/vkm]
Private e-scooter	0.464
Shared e-scooter	0.704

3.3.3 Use

The GHG emissions in the use phase of the e-scooter for a given lifetime mileage are shown in figure 34 below. Since the emissions scale linearly with the lifetime mileage, only the comparison between different electricity mixes is made. The scenarios "Belgian electricity" and "Average electricity" use the Belgian and global average electricity mix respectively. The constituents of these electricity mixes are shown in the previous section in table 9. The scenario "High carbon electricity" assumes that the electricity mix consists exclusively of electricity obtained through burning coal. Conversely, in the scenario "Green electricity" all the electricity is obtained through renewable resources.

The production of high carbon electricity creates twice as many GHG emissions per km as the production of the average global electricity mix. As the share of renewable energy in the global electricity mix increases – currently up to 29% compared to 20% in 2010 – these emissions will decrease further. The GHG emissions associated to the production of electricity in Belgium are much lower, primarily due to the larger share of nuclear energy and lower share of energy obtained through coal compared to the global electricity mix. As demonstrated in the figure, there is still room for improvement by working towards exclusively renewable energy.

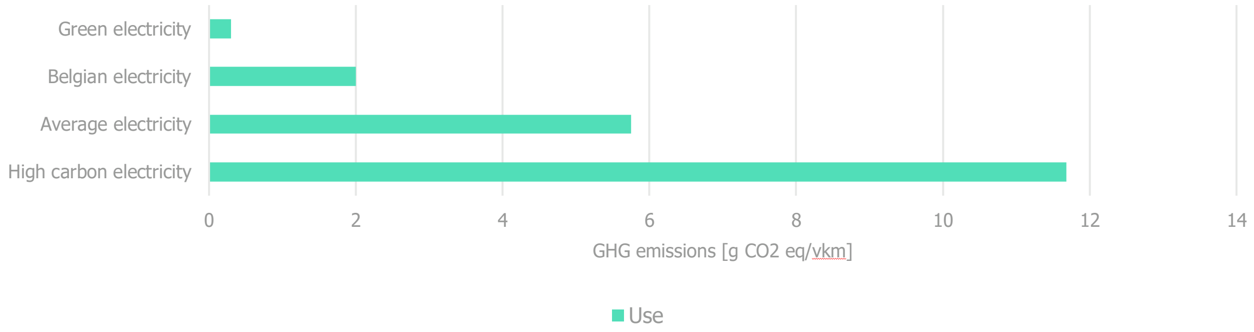


Figure 34: GHG emissions due to vehicle use.

3.3.4 Operational services

For the maintenance and redistribution of the shared e-scooters we use the numbers of the ITF report. The authors acquired these estimates through personal communication with shared e-scooter providers. It is assumed that the e-scooters are picked up for charging once every four days. The service vehicle makes a round trip of 45 km every day. Note that 45 km is an estimate for cities in the USA and may thus be a bit high for Belgian cities. However, we decided to remain on the safe side and maintained this estimate. Dividing the trip length by four results in a daily service vehicle trip of 11.25 km per e-scooter. Furthermore, a capacity of 10 e-scooters per van is assumed. The GHG emissions needed for operational services in different scenarios are shown in figure 35 below. In the best case scenario, electric vehicles are used for collecting and distributing the e-scooters and the GHG emissions are reduced by 85%. Not shown is a scenario in which EVs drive on exclusively green electricity, in which case there are no GHG emissions from driving the EVs around. However, while it is true that switching to EVs for operational services is the best single course of action, to absolutely minimize the emissions a combination of all improvements is ideal.

The figure also demonstrates the importance of the two most straightforward improvements: lowering the servicing distance, by installing more docking stations, and including more vehicles per servicing trip. The latter can be achieved by using swappable batteries, since they take up less space in the service vehicle. De-centralising the charging facilities can also be an option, but in terms of fire regulations probably less achievable.

Alternatively, if the daily distance travelled by the e-scooter is higher, the GHG emissions needed for operational services are lower per vehicle-km, since the service vehicle-km remain the same as in the base case but are divided by a larger amount of e-scooter kilometres. In other words, because our functional unit is g CO_2 equivalents *per vehicle km* a scooter that is used more is less polluting.

Additionally, in (Hollingsworth et al., 2019) a 7% decrease in GHG emissions is observed when the e-scooter collection is limited to those with a low battery state of charge. In (Kazmaier et al., 2020) a 12% decrease in the global warming potential is found when e-cargo-bikes are used to swap batteries. This reduction is much smaller than the claimed 56 to 81% by Dott in (Dott Blog, 2021). This difference can be explained by the fact that Kazmaier et al. consider a scenario where the e-cargo-bikes can transport 15 batteries over 20 km compared to a combustion van that transports 35 batteries over 50 km whereas Dott claims to have found a way of reducing the number of trips from warehouse to city by half.

In conclusion, while it is true that switching to EVs for operational services is the best single course of action, to absolutely minimize the emissions a combination of all improvements is ideal.

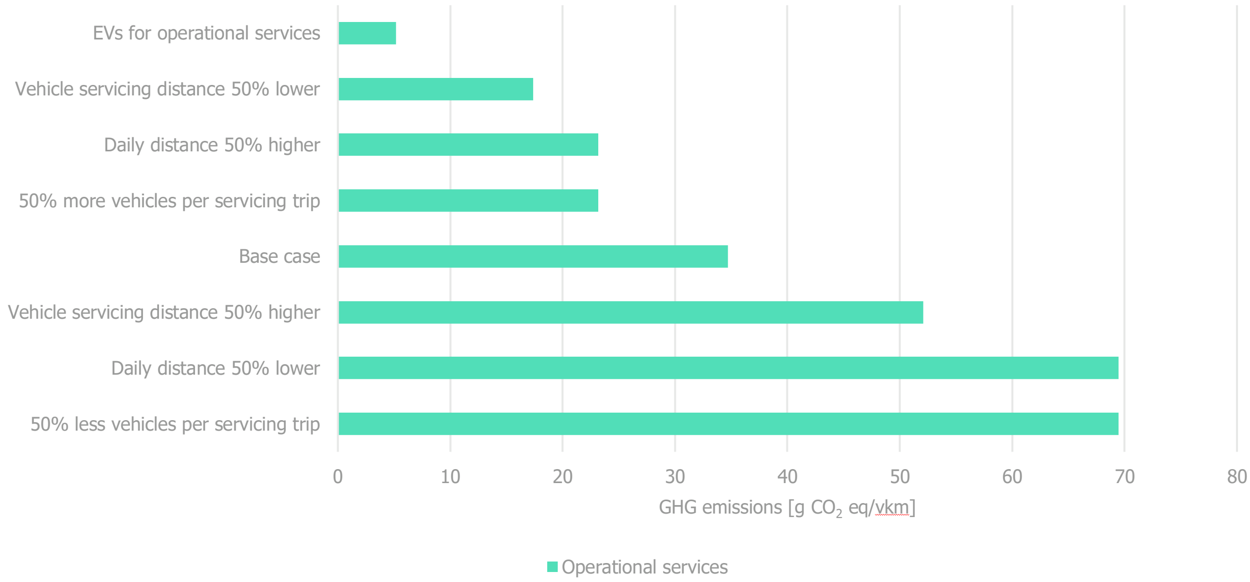


Figure 35: GHG emissions needed for operational services [g CO_2 eq/vkm].

In (EY, 2020) an independent LCA of the third generation shared e-scooter of Voi is performed by Ernst & Young. In the best case scenario, they found that the operational services only contribute to 3.5% of the total life cycle emissions compared to 43% found in the first ever life cycle assessment of shared e-scooters by (Hollingsworth et al., 2019). This reduction is due to a combination of the above discussed improvements: using exclusively renewable energy to charge the e-scooters and the fully electrified service vehicle fleet, optimizing the collection route to decrease the daily service distance by 30% and using swappable batteries which also enables more rides to be provided with the same fleet size thanks to a smaller down-time.

3.3.5 Infrastructure

The GHG emissions of the infrastructure component depend on the type of road the e-scooters are ridden on. Assuming drivers spend 20% of their time on bike lanes and 80% on urban roads, like in the framework proposed in (Cazzola & Crist, 2020), it yields GHG emissions of 9 g CO_2 eq/vkm. These emissions are due to maintenance and construction of roads. Although one could argue that e-scooters make use of existing infrastructure, these roads had to be constructed at some point in time. Therefore, it is only fair to attribute part of the emissions to all users of the infrastructure. Additionally, small damages to roads impact e-scooters more than other transport modes due to their smaller wheels, making maintenance of roads that much more important.

The GHG emission impacts related to the construction of docking stations are excluded from the system boundaries. It is conceivable that adding docking stations could lead to GHG emission impacts similar to the manufacturing of e-scooters themselves, due to requiring a comparable amount of materials and requiring more than one docking station to be available per e-scooter (Source: claim made for e-bikes in ITF report). It is plausible that the GHG emissions due to the construction of charging stations are eventually accounted for by the reduced emissions associated to the operational services, but this particular assessment falls beyond the scope of this study.

3.4 Interpretation

To interpret the results, the total carbon impact of e-scooters and the relative importance of each contribution are discussed in the next section. A sensitivity analysis is performed to deduce how the contributions change when certain parameters vary. Following the sensitivity analysis, the LCAs found in scientific literature are discussed. Last but not least, a scenario that takes into account **recent developments** is considered.

Secondly, the comparison is made between the life cycle GHG emissions of e-scooters and of other modes of transport. Based on the survey conducted in light of this project and an existing survey conducted by Brussels Mobility in Brussels, the environmental impact of e-scooters can be compared with the environmental impact of the average mode of transport that they replace.

3.4.1 Total carbon footprint of e-scooters

3.4.1.1 First generation

The total carbon impact can be found as the sum of all the contributions from the previous sections. The scenario "First generation" has all the base assumptions, namely a first generation shared e-scooter that:

- has a lifetime of 18 months,
- is driven 2900 km per year,
- is transported from Shenzen, China to Brussels by means of shipping and trucking,
- uses the average Belgian electricity mix,
- is serviced once every four days by a van with an internal combustion engine with a service vehicle round trip of 45 km (as discussed in 3.3.4),
- and requires urban roads and bicycle lanes to be constructed.

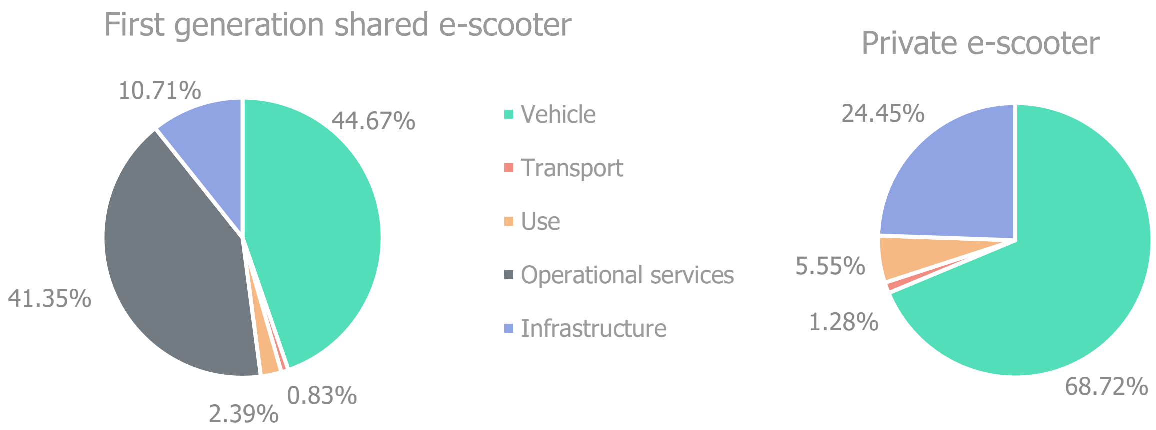


Figure 36: Relative share of the components in the life cycle GHG emissions of a first generation shared e-scooter and a private e-scooter.

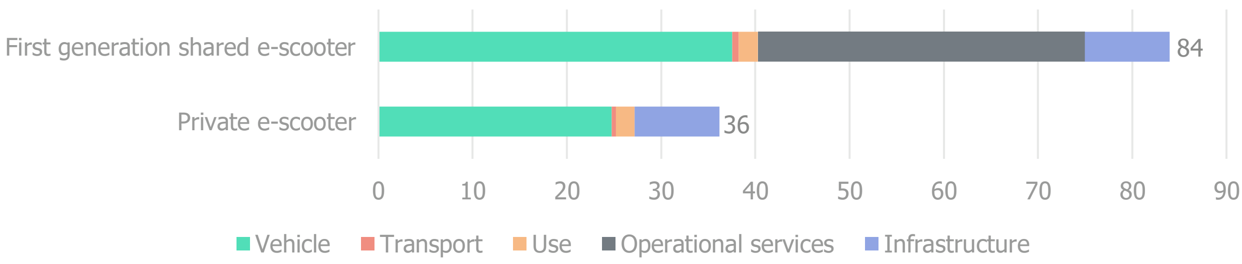


Figure 37: The life cycle GHG emissions of a first generation shared e-scooter and a private e-scooter in g CO_2 per vehicle-km.

This scenario is a realistic approximation of an early shared e-scooter service, based on scientific literature and interviews with shared e-scooter providers. Later in this section the parameters are updated to the situation nowadays with the use of more modern e-scooters. The sum of the life cycle GHG emissions in "First generation" comes to a total of 84 g CO_2 eq/vkm. The main contributions are due to manufacturing, assembly and disposal of the vehicle on the one hand and the operational services and maintenance on the other hand with a share of 44% and 41% of the total environmental impact respectively. For private e-scooters the operational cost becomes irrelevant, meaning that the vehicle component becomes even more dominant in the total life cycle emissions, as can be seen in figure 36. As a result, for private e-scooters the most environmental gains can be made through less carbon intense manufacturing processes. Note that the absolute values in the life cycle emissions (36 g CO_2 eq/vkm) are much lower for private e-scooters than those of shared e-scooters, as shown in figure 37, due to the assumed longer lifetime of 3 years, larger lifetime mileage of 6600 km and no need for operational services.

In both cases, the initial transport concerning the delivery of the e-scooter and the use of the e-scooter only make up tiny fractions of the life cycle emissions, as long as more than enough units can be shipped at the exact same time. Finally, the manufacturing of the materials and construction of the infrastructure contribute close to 11% and 24% to the total impact for shared and private e-scooters respectively, but can be ignored once the infrastructure is already in place, and this will largely depend on the available infrastructure and policy recommendations specifically targeted for e-scooters (e.g. requirement of docking stations increases the infrastructure component).

3.4.1.2 Newest generation

To take into account recent developments, the scenario "Newest generation" is now considered. To summarise, we assume that the newest generation of shared e-scooters:

- has a lifetime of **36 months**,
- is driven **3650 km** per year,
- is transported from Shenzen, China to Brussels by means of shipping and trucking,
- uses the average Belgian electricity mix,
- is serviced once every four days by an **electric van** with a service vehicle round trip of 45 km (as discussed in 3.3.4),
- and requires roads and bicycle lanes to be constructed for the sake of completeness.

These assumptions are a realistic approximation of a shared e-scooter service nowadays, based on the interviews with shared e-scooter providers and the sustainability report (Dott, 2022). The average trip distance is 2 km and with about 5 daily trips, the estimate of 10 km for daily mileage is obtained. Using electric vans for operational services is certainly the ambition of many shared e-scooter providers. The impact of this change is assessed in this scenario.

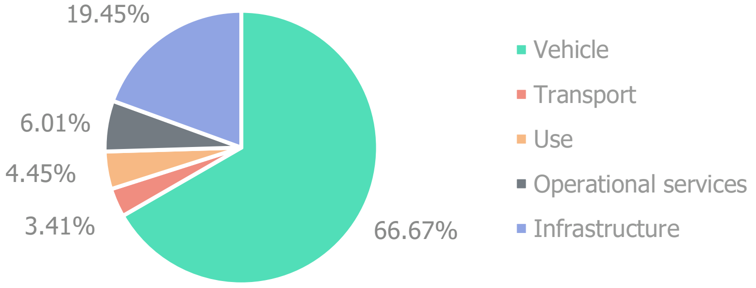


Figure 38: The relative share of the different components in the life cycle GHG emissions of the newest generation shared e-scooter.

Under these circumstances, the newest generation shared e-scooter has life cycle GHG emissions of 49 g CO_2 eq/vkm, compared to 84 g CO_2 eq/vkm for the first generation, as shown in figure 39 below. This large decrease is mainly due to a significantly longer lifetime (36 months vs 18 months), an increased daily mileage (10 km vs 8 km) and the use of electric vans instead of combustion vans for operational services. In this way, the relative share of the vehicle component once again becomes dominant, just like for private e-scooters. Consequently, once operational services have been optimized from an environmental standpoint, the remaining course of action for improvement focusses on less carbon intense manufacturing processes.

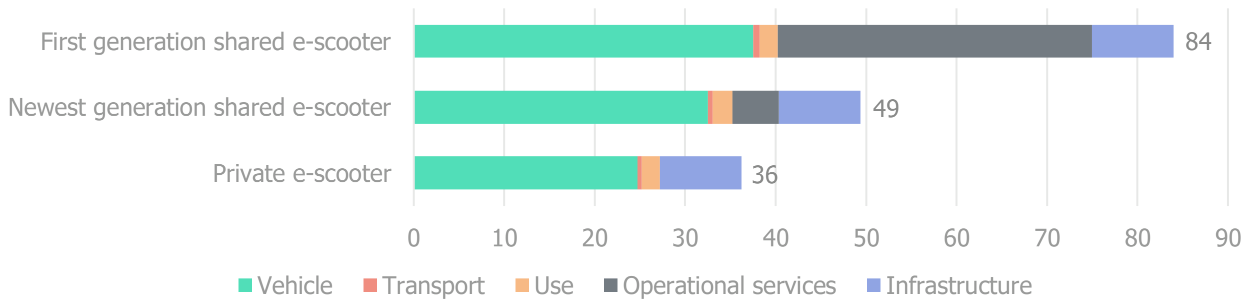


Figure 39: The life cycle GHG emissions of a first generation shared e-scooter, a newest generation shared e-scooter and a private e-scooter in g CO2 per vehicle-km.

3.4.1.3 Sensitivity analysis

Different scenarios are shown in figure 40 below, where the relative importance of each contribution and sensitivity to variations is portrayed. Each alternative scenario consists of one change compared to the base case, while the other parameters are kept fixed. Recall that the base case consists of a first generation **[newest generation]** shared e-scooter which:

- has a lifetime of 18 **[36]** months,
- is driven 2900 **[3650]** km per year,
- is transported from Shenzen, China to Brussels by means of shipping and trucking,
- uses the average Belgian electricity mix,
- is serviced once every four days by a van with an internal combustion engine with a service vehicle round trip of 45 km (as discussed in section 3.3.4),
- and requires urban roads and bicycle lanes to be constructed.

A sensitivity analyses was not separately performed for private e-scooters, since the components are largely the same as shared e-scooters, except for the operational services. Changes observed within shared e-scooters, excluding operational services, can therefor serve as a indication for private e-scooters as well.

Based on these scenarios, the following key insights emerge:

- The life cycle GHG emissions per vehicle-km are very sensitive to changes in the average daily distance travelled by e-scooters. This is because the vehicle and operational services components are much larger than the use component and thus vary greatly per vkm. In other words: the benefits of using the e-scooter more outweigh the direct impact from the higher energy use.
- Similarly, changes in the average lifetime of the e-scooter have significant impacts on the GHG emissions. A longer lifetime usually corresponds to a larger lifetime mileage and lower emissions per vkm.
- The impact of the operational services component can be decreased by reducing the servicing distance and increasing the number of e-scooters per servicing vehicle trip. In short, both of these improvements minimise the ratio of servicing vehicle km to e-scooter km, thus making the servicing trips more efficient.
- A switch to electric service vehicles is another effective way of lowering the GHG emissions associated to maintaining an operational fleet of shared e-scooters. Similarly, dedicated cargo bicycles can be equally effective, provided that they have a high enough usage rate to offset the initial emissions due to manufacturing and assembly (Cazzola & Crist, 2020).
- Technological advancements such as low carbon Aluminium smelting can have significant impacts on the GHG emissions per vkm. In this way the dominant contribution of the vehicle component can be reduced.
- An increase in vehicle weight has a negative impact due to the additional required materials. Conversely, making the vehicle lighter can offer significant reductions in life cycle emissions. However, a lighter vehicle may be less durable than a heavier, sturdier vehicle, especially with shared vehicles. Given the importance of a high lifetime, the higher initial emissions of a heavier vehicle may well be worth it in the long term.
- The infrastructure component is relatively small and only has a small contribution to life cycle GHG emissions, mainly because not much additional infrastructure is required and existing infrastructure lasts a very long time.
- The contribution of the transport component to the life cycle GHG emissions is negligible. The reason for this is the efficient transport by ship from China to Belgium in large quantities. If a larger part of the journey would have been made by truck, then the GHG emissions per km would increase. However, largely dependent on the number of items shipped is it staying relatively small all things considered. In particular, the low impact of the transport implies that manufacturing the e-scooters in Europe or even Belgium would not directly have a big impact on the total emissions due to lower transport emissions. It is known that (battery) manufacturing plants for electric vehicles are being constructed in Europe, so e-scooters could also be produced in Europe over time. Harsher production emissions regulations in Europe compared to China can potentially offer significant reductions.
- Finally, using green electricity to charge the e-scooters only has a small benefit (in Belgium). The life cycle GHG emissions due to charging are already small, due to the relatively low carbon Belgian electricity mix compared to the global average, relative to the contributions of the other components.

For example, in a worst case scenario, in which a first generation e-scooter has a 50% reduced lifetime, a 50% reduced annual mileage and is 25% heavier, yields an emission of 271 g CO_2 equivalent per vehicle km. Comparing this with the life cycle GHG emissions of a private car with internal combustion engine of 162 g CO_2 eq per passenger-km shows how polluting a less often used e-scooter actually is. Conversely, in a best case scenario where low carbon aluminium melting is used in the manufacturing of a first generation e-scooter with a 50% increased lifetime and a 50% increased annual mileage, the GHG emissions are down to 14.8 g CO2 eq/vkm. These observations demonstrate the sensitivity of the vehicle component to the lifetime and mileage of the vehicle.

These insights indicate which higher order design improvements e-scooter manufacturers can make. They should aim to construct lightweight, but strong and durable vehicles, by means of less carbon intensive manufacturing processes. During the interviews conducted with e-scooter sharing providers, the providers mentioned precisely these ambitions. Additionally, as time passes and more data becomes available covering components that break most often, manufacturers can actively redesign these imperfections to make them more robust.

Since a sensitivity analysis is focussed on the relative changes, the results of the newest generation are very similar to those of the first generation shared e-scooters. The main difference lies in the fact that the base case scenario now has lower life cycle GHG emissions of 64 g CO_2 eq/vkm compared to 84 g CO_2 eq/vkm. The assumptions in the base case scenario are identical except for a higher vehicle lifetime (36 months) and a higher annual mileage of 3650 km, compared to respectively 18 months and 2900 km. While the relative changes due to varying parameters are similar for both generations, the absolute differences are smaller for the newest generation. This observation once again confirms that vehicle lifetime and mileage are the most impactful parameters.

There are some slight differences regarding the impact of the different scenarios. Using zero carbon electricity for the newest generation reduces the life cycle GHG emissions by 4% while using high carbon electricity raises the emissions by 16%, compared to respectively 3% and 11% for the first generation. The increased importance of using low carbon electricity can be explained by the fact that the vehicle component is much smaller due to the assumed higher vehicle lifetime and mileage, so the use component becomes more prominent.

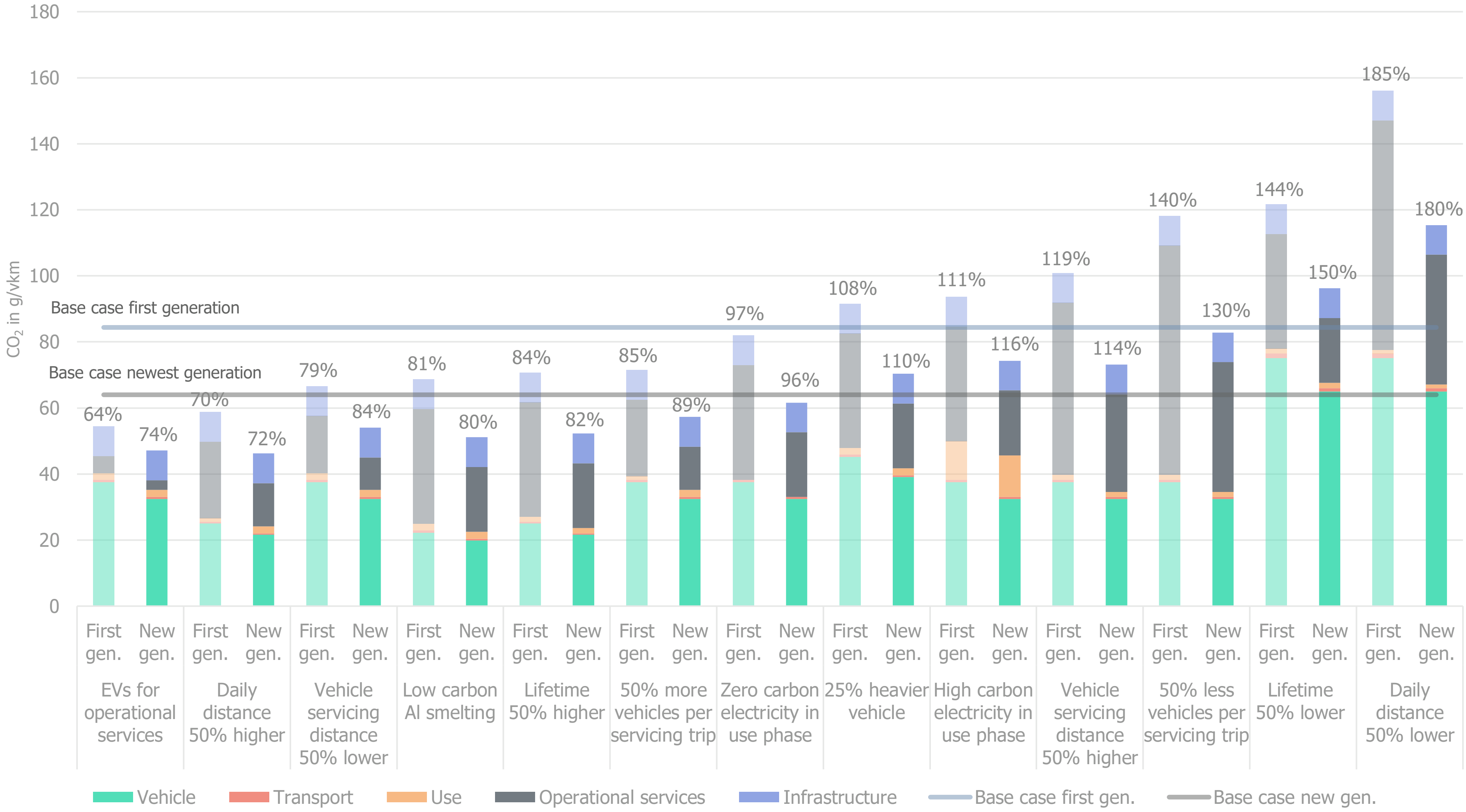


Figure 40: Sensitivity of the life cycle GHG emissions of the first and newest generation shared e-scooters to changes in parameters. Source: adapted numbers from (Cazzola & Crist, 2020)

A range of life cycle GHG emissions of shared e-scooters found in various peer-reviewed scientific articles is summarised in table 11 below, together with the most important findings and assumptions. As discussed below, the impact of the different parameters explored in 40 can be seen in practice.

(Hollingsworth et al., 2019) found nearly identical life cycle GHG emissions of 125 g CO_2/vkm as in the ITF report. In their LCA the operational services component contributes 43% to the global warming potential. This larger than usual contribution is due to an above average collection distance and the use of carbon-intense servicing vehicles.

(Kazmaier et al., 2020) found life cycle GHG emissions of 165 g CO_2/vkm, 35% higher than the first generation central case in the ITF report due to a heavier vehicle with a larger battery. They concluded that e-scooters do not currently contribute to an eco-friendly and clean mobility – which differs from our findings, as will be discussed in the next section – since they produce more CO_2/vkm than the modes of transport they replace which reaffirms the earlier findings of (Hollingsworth et al., 2019). Therefore, it can be hypothesised that if e-scooters were more widely used and replaced more carbon-intensive modes of transport, they might become beneficial. However, Kazmaier et al also found that e-scooters do not interest those who have not yet used it as a mode of transport, thus requiring some sort of incentivisation in order to attract new users.

(Severengiz et al., 2020) found life cycle GHG emissions similar to those of (Hollingsworth et al., 2019), only 17% lower due to a shorter servicing distance. In their best case scenario e-scooters have a global warming potential of 64 g CO_2 per passenger-km, compared to 8g, 40g and 58g for bikes, e-bikes and trams respectively.

(Moreau et al., 2020) found life cycle GHG emissions of 131 g CO_2/vkm, which is larger than the average GHG emissions per passenger-km of 110 g CO_2/pkm of the displaced modes of transport. The authors conclude that shared e-scooters become a green mobility solution once they have a lifetime of at least 9.5 months. Private e-scooters on the other hand have much lower life cycle GHG emissions of only 67 g CO_2/vkm due to a lighter frame and not requiring operational services for charging.

The more recent papers (de Bortoli, 2021) and (Licata, 2021) found much lower life cycle GHG emissions of 61 and 36 g CO_2/vkm respectively due to higher assumed and observed lifetimes and lifetime mileages. It is reasonable to assume that, as technology advances, the lifetimes of e-scooters gradually increase. Similarly, a daily mileage of 10-20 km is a fair assumption, as pointed out by an e-scooter sharing provider in Licata, 2021. However, a daily average of only 4.6 km was found over a period of 510 days in Brussels, during which there were two lockdowns. Hence caution is warranted when dealing with data obtained during extraordinary circumstances. The optimistic scenario in Licata, 2021 in which each e-scooter achieves a daily mileage of 50 km has a greatly decreased global warming potential but is based on a somewhat unreasonable assumption. Nevertheless if e-scooter sharing services become more popular higher daily mileages can be reached and correspondingly the GHG emissions per vehicle-km will decrease.

Overall, the life cycle GHG emissions found in the scientific literature are significantly higher than the best case scenario emissions reported by e-scooter sharing providers. The larger life cycle emissions estimates in the scientific literature are primarily due to shorter assumed lifetimes and mileages. In (EY, 2020) the life cycle GHG emissions of the Voi 3 e-scooter are estimated at 35 g CO_2/vkm, assuming a lifetime of 24 months, high scooter utilization, 100% renewable energy and the use of e-cargo bikes to swap batteries. Similarly, Dott reports a current best case scenario of 40 g CO_2/vkm for their vehicles in Lyon, assuming a lifetime of 36 months, but not deducing emissions thanks to recycling, unlike EY. More conservatively and more in line with the scientific literature, a global average of 100 g CO_2/vkm is stated in (Dott, 2022). This global average is more than double of the emissions in the best case scenario, due to not every operational fleet being fully electric and varying operational services and transport distances in different parts of the world. Nevertheless, Dott intends to further decrease the best case scenario GHG emissions to 20 g CO_2/vkm by 2025 via increasing the e-scooters lifespan to 5 years, decreasing the loss rate to 0.5% and assembling vehicles in Europe to cut down on transport emissions among other efforts. However, these figures could not be checked with actual real-life performances.

The main numbers from our analysis – 84 g CO_2/vkm and 64 g CO_2/vkm for the first and newest generation shared e-scooter respectively and 36 g CO_2/vkm for private e-scooters – fall in between the rather conservative estimates in the scientific literature and the optimistic, best case scenarios reported by shared e-scooter providers. This is a consequence of our assumptions; the vehicle lifetimes and mileages used also fall in between the conservative, early estimates in the scientific literature and the optimistic, more recent estimates of shared e-scooter providers.

Table 11: Life cycle GHG emissions of shared and private e-scooters found in scientific literature.

Source	Country	Private / shared	gCO_2 eq/vkm	Vehicle component	Comments / Conclusions
(Hollingsworth et al., 2019)	USA	Shared	125	50%	• Daily collection for charging and redistribution contributes 43%. • Main improvements: fuel-efficient vehicles, only collecting scooters with low battery and reducing collection distance.
(Kazmaier et al., 2020)	Germany	Shared	165	73%	• Assumption of robust e-scooter with larger battery; main impact from aluminium frame and production of battery. • Best case scenario = 46 g CO_2 eq/vkm assuming a lifetime of 15 months. • Most important factors in the LCA are the lifetime, swappable batteries and electricity mix from renewables.
(Severengiz et al., 2020)	Germany (Berlin)	Shared	77	63%	• Assumed a 2 year lifetime. • A 6 month lifetime gives 237 g CO_2/vkm. • Best case scenario still worse than bikes, e-bikes and trams.
(Moreau et al., 2020)	Belgium (Brussels)	Shared, private	131 (shared) 67 (private)	73%	• Assumed a 7.5 month lifetime. • Lifetime of 9.5 months needed to be a green mobility solution • At a lifetime of 3.4 years the operational services component becomes dominant.
(de Bortoli, 2021)	France (Paris)	Shared, private	61 (shared) 42 (private)	79%	• Assumed a 24 month lifetime. • Daily mileage of 10 km.
(Licata, 2021)	Belgium	Shared	36	47%	• Assumed a 24 month lifetime. • Daily mileage of 20 and 50 km give rise to 80 and 36 g CO_2/vkm resp.

3.4.2 Comparison with other modes of transport

To get a view on the environmental impact of private and shared e-scooters in the larger picture of mobility, the comparison with the life cycle GHG emissions of other modes of transport is made in figure 41. As has been pointed out in the previous section, the transport needed for the initial delivery of vehicles is negligible and thus left out of the discussion. Note that the emissions are calculated per passenger-km (pkm) since some modes of transport can carry multiple passengers at once. The abbreviation ICE stands for internal combustion engine. The lifetimes, mileages and average number of passengers of each mode of transport are summarized in table 12 below.

It has to be noted that the calculations for an EV were made, based on the data of (Cazzola & Crist, 2020) and updated with the Belgian electricity mix (which is in general less carbon intensive compared to countries such as the US) and electric vehicle fleet.

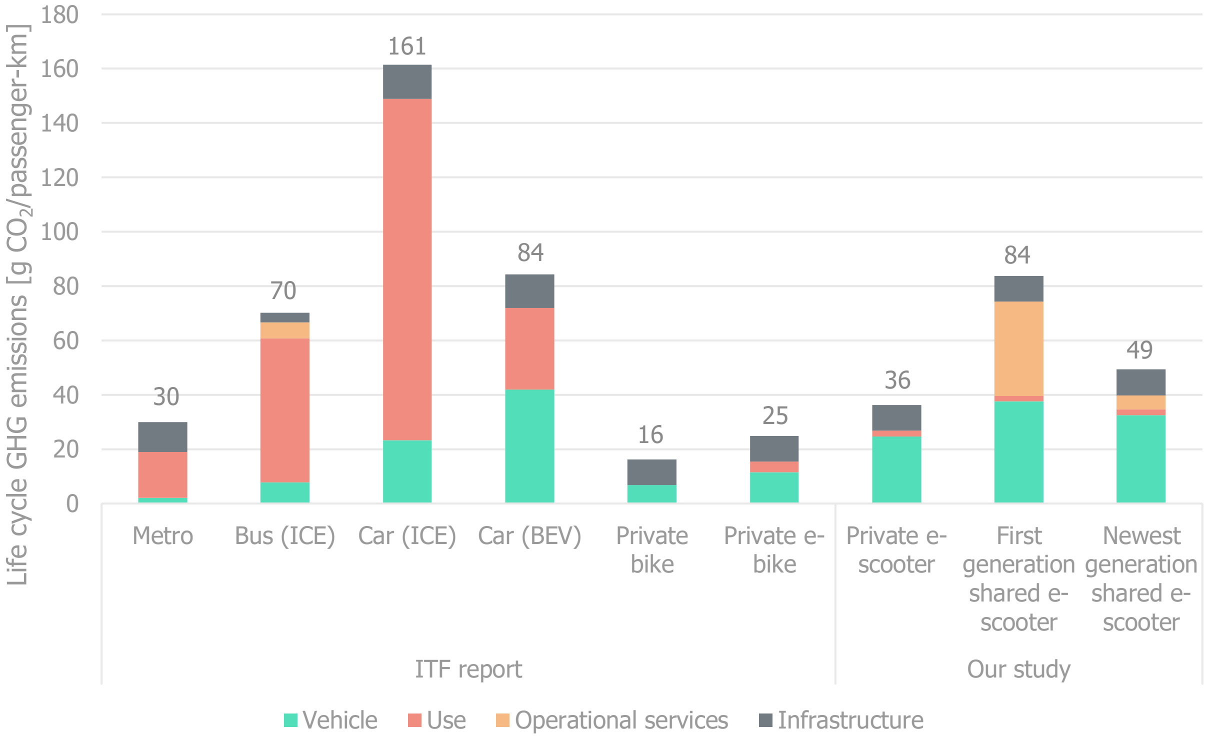


Figure 41: Life cycle GHG emissions of different modes of transport per passenger-km. Numbers based on (Cazzola & Crist, 2020) and our own calculations.

Table 12: Lifetime, annual mileage and average number of passengers of different modes of transport. Numbers based on (Cazzola & Crist, 2020) and interviews with e-scooter sharing providers.

	Vehicle lifetime [years]	Annual mileage [km/year]	Average number of passengers
Metro	40	66000	190
Bus	9	44000	17
Car (EV and ICE)	15	12100	1.5
Private bike	6	2400	1
Private e-bike	6	2400	1
Private e-scooter	3	2200	1
First generation shared e-scooter	0.8	2900	1
Newest generation shared e-scooter	3	3650	1

In (Moreau et al., 2020), the authors analysed a survey conducted by Brussels Mobility on the use of e-scooters to know the relative share of the displaced modes of transport. They found these shares by analysing the responses to the question "Before the arrival of e-scooters, what mode of transportation would you have used for the same type of trips?". However, users may utilise their e-scooters for many types of trips for which they may have used different modes of transportation before the arrival of e-scooters. Hence this one question does not encompass the whole situation, which should be kept in mind when analysing the results. Similarly, the modal share can differ greatly from one location to the other, so care should be taken when attempting to generalise results.

In our mobility study however, we found that e-scooters mainly impact car trips, while not affecting bicycle and public transport trips. This finding was not determined trip specific, but based on overall mode choice, making the finding more robust in terms of deliberate mode choice over longer period of time (i.e. if it is determined trip specific, a possibility arises on biasing the modal split determination. This because it does not mean that a specific person makes a trip now by car, that this person always makes the same trip by car). This finding is important, since e-scooters have overall more GHG emissions compared to bicycles and walking, but since car use is mainly replaced, more benefits can be seen compared to estimations of other studies.

The results from the study of (Moreau et al., 2020) for both shared and private e-scooters are summarised in Table 13. "Additional trips" corresponds to the users who would not have made the trip otherwise. The analysis shows that people who use a private e-scooter more often do so to replace car rides, whereas shared e-scooters more often replace walking. As the authors point out, these differences could be explained by the fact that private users tend to use their e-scooter to commute to the workplace whereas shared e-scooters are sometimes used for leisure purposes. From an environmental standpoint, it would be ideal if e-scooters mostly replaced carbon-intense modes of transport such as cars rather than the environmentally friendly public transport, biking and walking. Such a trend is observed in the USA, where the modal share is very different.

Table 13: Mode of transportation displaced by the use of shared and private e-scooters. Source: (Moreau et al., 2020).

Transport mode displaced	Shared users	Private users
Public transportation	29.2%	30.2%
Car	26.7%	28.4%
Walking	26.1%	21.1%
Bicycle	14.2%	15.5%
Electric bicycle	1.5%	1.6%
Additional trips	1.8%	1.5%
Other	0.1%	1.1%
Motorcycle	0.4%	0.6%

The average modal share displaced by the use of shared e-scooters has life cycle GHG emissions of 60 g CO_2/pkm, 29% lower than the first generation of shared e-scooters and 22% higher than the newest generation of shared e-scooters (in which the effect can potentially be higher, if the larger replacement of car use would be taken into account). The average modal share has emissions which are much lower than the first generation of shared e-scooter due to the large shares of walking and biking, which have no and very little emissions respectively. The newest generation of shared e-scooters performs better than the average modal share, given that it has a lifetime of at least 36 months, is driven at least 10 km daily and is serviced by an electric van or electric bike. It is important to note that e-scooters remain more polluting than walking and biking, but form more environmentally friendly alternatives to cars.

4 Safety and riding behaviour

As mentioned in the introduction of this study, a better understanding of riding behaviours and conflicts is necessary for e-scooters, bicycles and e-bikes in shared spaces. For this a behavioural and conflict observation study was performed.

The purpose of this study is not to solely determine who is to blame for a conflict. The idea behind the behavioural and conflict observation study is to better understand the behaviours and conflicts to actively improve the safety situation in shared spaces. Further, it will be used to accurately determine if the prejudices are founded or not. Based on these observations, recommendations can be made to actively improve the safety of road users in shared spaces.

4.1 Methodology

4.1.1 Site selection

For this study, four locations in Brussels were selected based on a site visit and earlier mentions of considerable e-scooter presence. Since Brussels can be seen as a pioneer for e-scooters, focus was laid on the city of Brussels. Other reasons are the high usage numbers in the national capital (confirmed by our questionnaire), many shared spaces with e-scooter presence, and the possibility to apply best practices from Brussels in other Belgian regional cities.

The four locations that were selected for this research were divided between pedestrian zones and shared public spaces that are not categorised as pedestrian zones. This resulted in the following four locations:

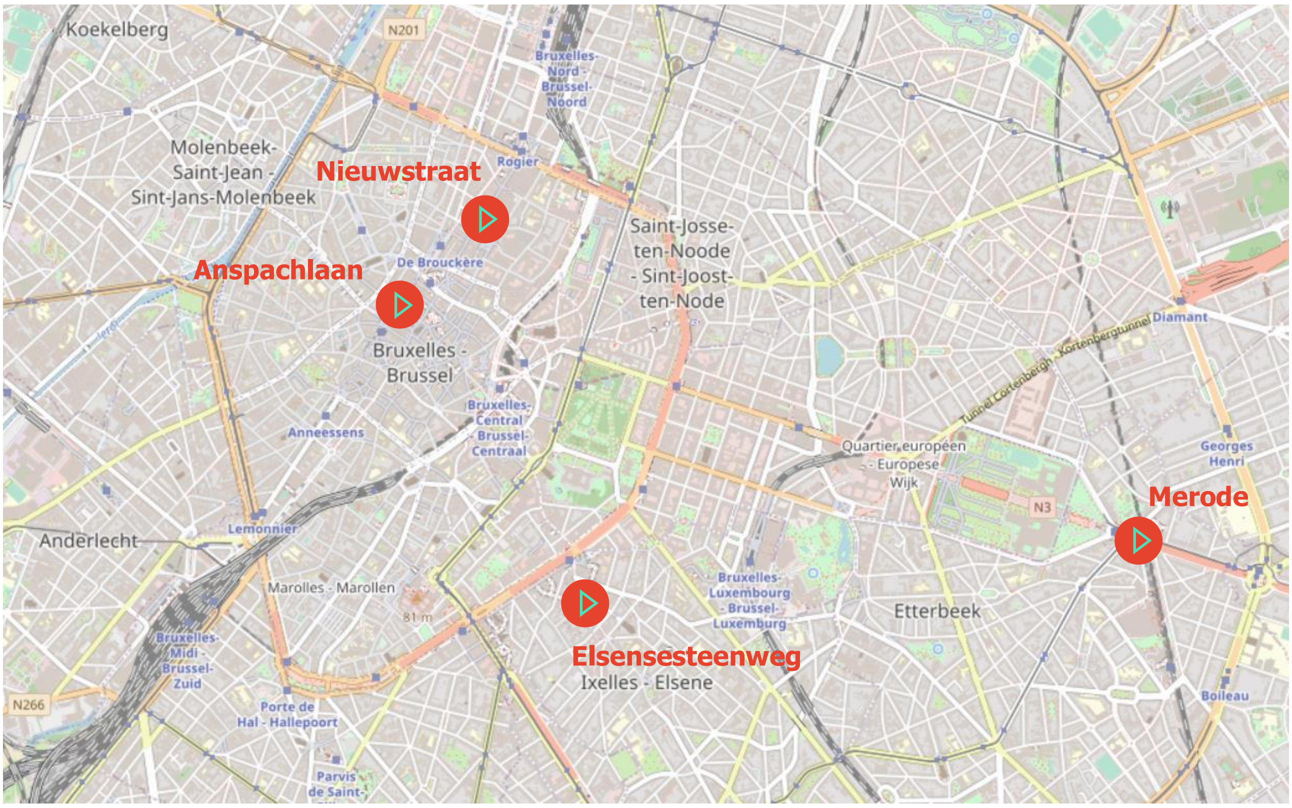


Figure 42: Behavioural and conflict observation locations (source: OpenStreetMap)

Shared public space	
Elsene	Merode
near intersection Elsensesteenweg x Francartstraat	near intersection Tervurenlaan x Keltenlaan
	
Pedestrian zones	
Nieuwstraat	Anspachlaan
near intersection Nieuwstraat x Koolstraat	near intersection Anspachlaan x Kiekenmarkt
	

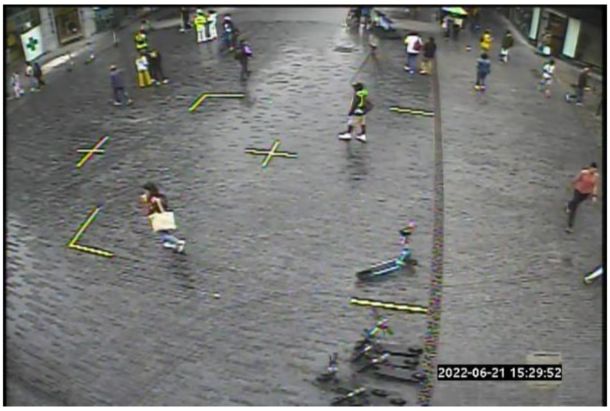
4.1.2 Data collection

To be able to perform the behavioural and conflict observations, video images were collected through a temporary camera system. This camera is a mobile and autonomous system with telescopic pole with a maximum height of 6 meters and low resolution to make it impossible to recognize faces and number plates. In total, 67 hours of video material was collected for each location. The videos were collected in parallel on all locations on predetermined hours of interest on different weekdays:

– Wednesday 22/06/2022	– 7.00am until 8.00pm (13 hours)
– Thursday 23/06/2022	– 7.00am until 8.00pm (13 hours)
– Friday 24/06/2022	– 7.00am until 11.59pm (17 hours)
– Saturday 25/06/2022	– 12.00am until 3.00am (3 hours) – 9.00am until 8.00pm (11 hours)
– Sunday 26/06/2022	– 10.00am until 8.00pm (10 hours)

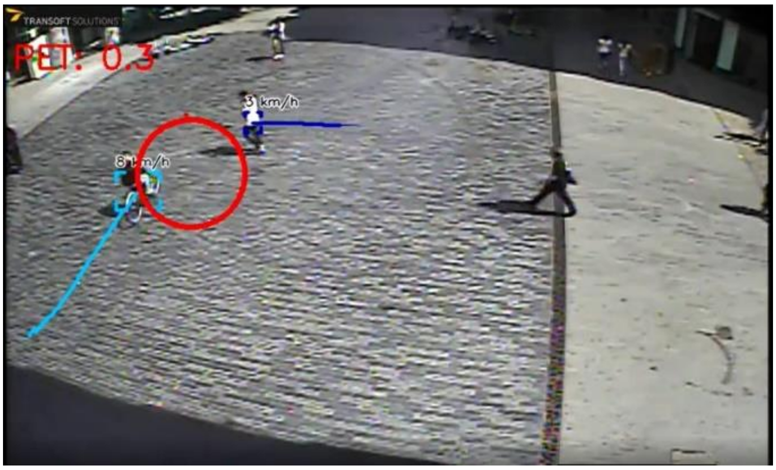
Due to the large number of video hours collected, two different data processing strategies were pursued. On one hand a manual coding of images was performed on 10 hours of video footage of each location, divided over different time periods and different days, to be able to determine the number of riders on an e-scooter. On the other hand automated software was used (i.e. the behaviour and conflict observation software package TrafxSAFE Plus from Transoft Solutions), to extract speeds, number of users, and conflict information.

In order to accurately determine conflicts and behaviours, a 3D-laser scan was taken of each location and matched with the camera's vision (= calibration). The 3D-laser scan captures all real-life measurements on location to counter deformation on the video images. This was done by adding calibration points on the ground by means of tape, which could afterwards easily be removed to avoid an impact on behaviours. That way, different points on the camera could be matched with the same points on the 3D-laser scan. As a result, distances, speed, acceleration, deceleration, etc. can be measured, to determine conflict indicators.



Whilst the behavioural observation gives more insight into compliance towards a correct use of e-scooters, bicycles and e-bike in shared spaces in Brussels, the conflict observation focuses specifically on conflicts between the different road users in the shared space. Below an overview is given of the information that was extracted and coded with codebooks based on the different data processing methods.

- Behavioural observation (manual coding of the number of users on an e-scooter):
  - Date and time
  - Experimental site
  - Type of e-scooter (electric shared, electric private, non-motorised, unknown)
  - Number of people on the same e-scooter (1 person, 2 persons, more than 2 persons, unknown)
- Behavioural observation (with TrafxSAFE software):
  - Date and time
  - Experimental site
  - Type of road user (pedestrian, cyclist, e-scooter, other motorised vehicles)
  - Median speed
- Conflict determination (with TrafxSAFE software)
  - Safety indicator type (Time to collision 'TTC' or Post-Encroachment Time 'PET')
  - Safety indicator value (Time in seconds for TTC or PET)
  - Total number of detected road users
- Conflict observation (severe conflicts with TrafxSAFE software)
  - Date and time
  - Speed limit (8km/h for pedestrian zones and 25km/h outside pedestrian zones)
  - Type of road users (pedestrian, cyclist, e-scooter)
  - Median speed and conflict speed
  - Safety indicator type and value (Time to collision 'TTC' or Post-Encroachment Time 'PET')



Based on these raw coded variables the following information was extracted on behaviours and conflicts to perform a detailed analysis for each of the four locations:

Behavioural observation	Conflict observation
– Type of road users and their share – Ridden speeds – Speed compliance depending on the shared space (pedestrian zones or not) – The number of riders present on an e-scooter	– The number of interactions observed – The proportion of conflicts over the number of road users and interactions – The type of road users that are involved in these conflicts – Speed compliance within conflicts

As stated by Martensen et al. (2021) in a literature review, conflict observations have a relatively long tradition in traffic safety research. The application on vulnerable road users has increased in recent years. Conflict observation is based on interactions between road users. An interaction can be described as 'a situation in which two road users arrive at a location with such closeness in time and space that the presence of one road user can have an influence on the behaviour of the other' (De Ceunynck, 2017). These interactions can result into a conflict, when both road users come in very close contact. Two different surrogate safety measure indicators are often used to determine the presence of a conflict and its degree. The indicators are called: 'Time-to-Collision (TTC)' and 'Post-Encroachment Time (PET)', and are derived based on the speed of the road users and their distances from each other.

Time-to-Collision is defined as 'the time remaining until a crash between the vehicles would occur if they continued on their present course at their present rates' (Hayward, 1972). The TTC becomes smaller as long as two road users remain on an collision course, and increases in size when they adapt their course. The value seizes to exist when (one of) both road users change their course to a degree that they are not on a collision course anymore. The minimum of this value is also described as $TTC_{min.}$

Post-Encroachment Time is defined as 'the time between the moment when the first road user leaves the path of the second and the moment when the second reaches the path of the first' (Johnsson et al., 2018). With this PET, road users are not on a collision course, but nearly miss each other. In fact, PET indicates the extent to which both road users miss each other. The smaller the PET-value becomes the nearer both road users missed each other. For this indicator, only one value exists.

Given the large number of video hours collected and large number of interactions possible in these shared public spaces, manual coding of video footage to derive these indicators, was not feasible in this study. As a solution, automatic video processing software of 'Transoft Solutions TrafxSAFE Plus' was used, which claims to offer a good and reliable solution for analysing large data sets. Furthermore, the software is able to easily identify the different types of road users present on the locations.

In fact, Martensen and colleagues recently performed a conflict observation study in pedestrian areas in Belgium by means of this automated software. They indicated that, while the accuracy of the classification of road users by the TrafxSAFE software and the chosen conflict indicators by that same software do not reach 100% accuracy, the accuracy is high enough to process large amounts of video data, which is a very demanding and long lasting task. They further concluded that TTC is not necessarily the most appropriate surrogate safety measure for conflict observation with vulnerable road users.

However, Johnsson et al. (2018) found after a validation study that it is difficult to compare and discuss the validity of different surrogate safety indicators for vulnerable road users. They highlight that careful consideration is necessary when a suitable indicator has to be selected. Since no specific surrogate safety indicators were brought forward, and each of the indicators show their limitations, this study chose to remain with TTC and PET for this conflict observation through automatic video processing software. To add, while a risk remains on possible missed conflicts, manual processing of videos imposes the same risk as well.

To safely speak of an interaction, a maximal TTC or PET of 4.5 seconds was used conform the methodology of (Martensen et al., 2021). Larger values were excluded since an influence of the course of road users is expected to be low at these high values. In order to categorize a conflict as 'severe', thresholds of $TTC_{min} < 1.5s$ and $PET < 1.0s$ are often used in conflict observation research (Brown, 1994; Pulvirenti et al., 2021; Van der Horst, 1990). As a result, these thresholds were also selected in this study.

4.2 Behavioural analyses

4.2.1 Number of vulnerable road users

During the behavioural observation, a large number of vulnerable road users were counted in the shared spaces. Here, differences between the four locations can be observed as shown in figure 43.

For all four locations, a high share in pedestrians is observed. In fact, these pedestrian counts can be seen as the exact determinant for categorizing the four shared spaces. In the Anspachlaan and Nieuwstraat, the share of pedestrians within all vulnerable road users is the highest (i.e. between 92.5% and 97.7%). On the other hand, are pedestrians still largely present in Merode and the Elsensesteenweg, be it to a lesser extent (i.e. between 59.2% and 75.5%). Because of this, in general, a split can be seen between the two pedestrian zones with a very high share of pedestrians (i.e. Anspachlaan and Nieuwstraat) and the other two regular shared spaces (i.e. Elsensesteenweg and Merode).

The share of bicycle users within all counted road users is the second highest, ranging from 19.6% and 36.7% in the regular shared spaces, to 1.6% and 5.5% in the pedestrian zones. The share of e-scooter users is the lowest in all four zones ranging from 4.1% to 5% on the regular shared spaces and 0.7% to 2% in the pedestrian areas. In absolute numbers, the regular shared space at the Elsensesteenweg has more cyclists and e-scooter users compared to the other sites. Also at the Anspachlaan (pedestrian zone), high counts of cyclists and e-scooter users were observed, while Merode and the Nieuwstraat have lower counts. A complete overview of these road users observed can be found in the figure below. Only vulnerable road users were taken into account, while motorised vehicles were left out.

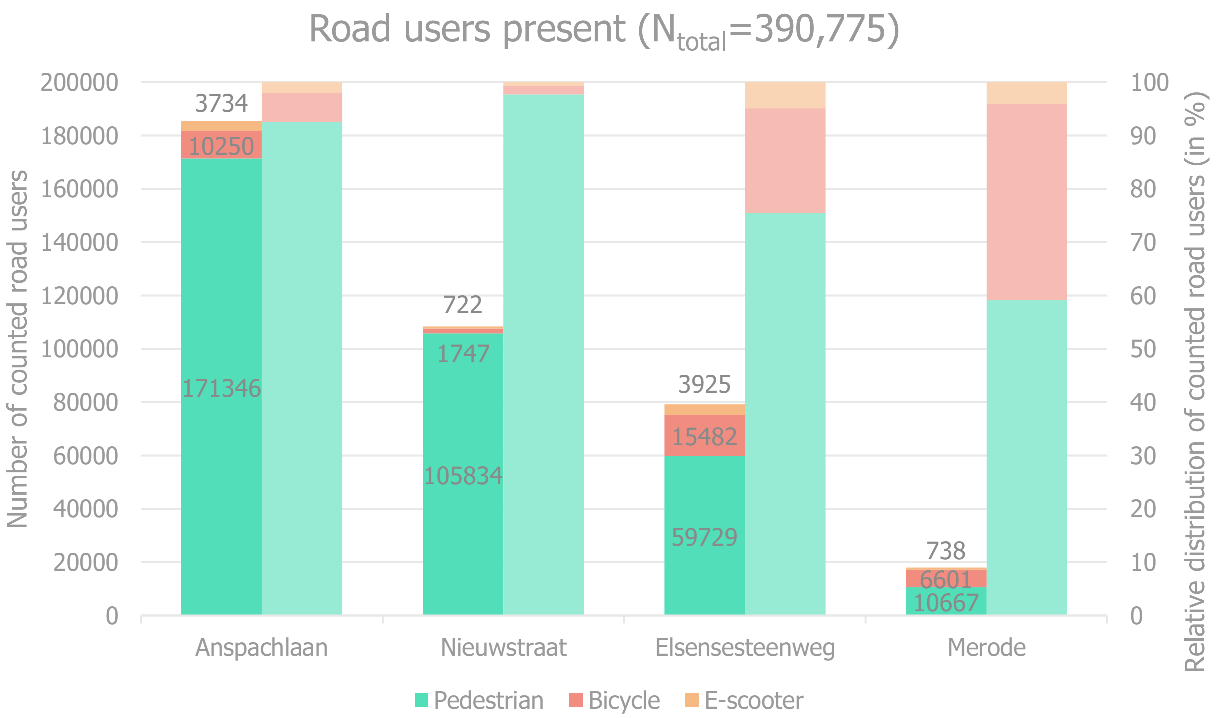


Figure 43: Number and share of vulnerable road users observed on the four test locations

An hourly distribution of the presence of cyclists and e-scooter users is displayed in figures 44 and 45. Given the shorter camera observation period on regular weekdays (i.e. 7a.m. to 8p.m.), a Friday was used for this distribution. On Friday 24/06 the camera observation lasted from 7a.m. to midnight.

In general, higher peaks in bicycle and e-scooter users were observed in the morning between 8a.m. and 10a.m and in the evening between 5p.m. and 7p.m., corresponding to the traffic rush hour. However, user counts already start creeping up as from 2p.m. in the afternoon. Here, differences between the four locations can also be observed, shown in the subsequent figures.

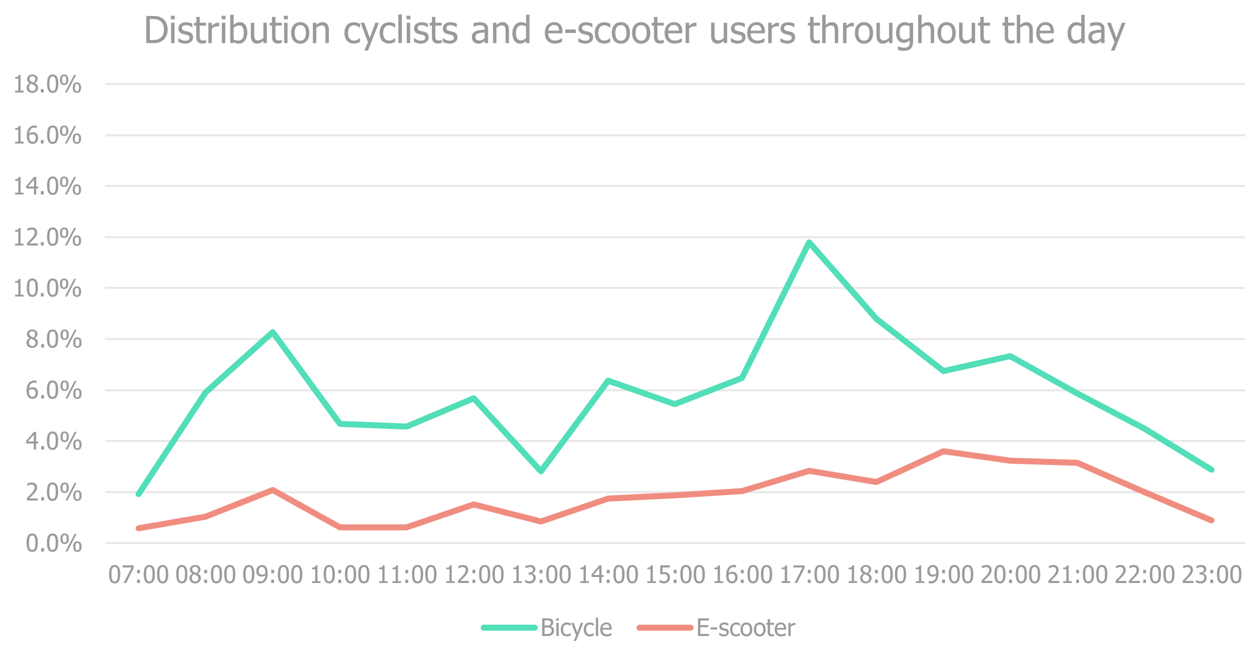


Figure 44: Distribution of cyclists and e-scooter users throughout the day taken together from the four test locations

While a peak of bicycle and e-scooter users is present between 8a.m. and 10a.m for all four locations, in the evening a different pattern can be observed. In the regular shared spaces, peak presence of cyclists and e-scooter users takes place between 5p.m. and 7p.m.. However, in the pedestrian areas, peak user shares are observed later in the evening between 6p.m. and 8p.m., and even a bit later as well. It is possible that this shift is related to a high pedestrian presence in these pedestrian areas during peak hours, therefor leading to a choice of cyclists and e-scooter users to avoid the area at peak pedestrian presence (especially at the Nieuwstraat). However, it is possible that this distribution is not fully representative for regular weekdays, since a Friday was used to calculate these distributions.

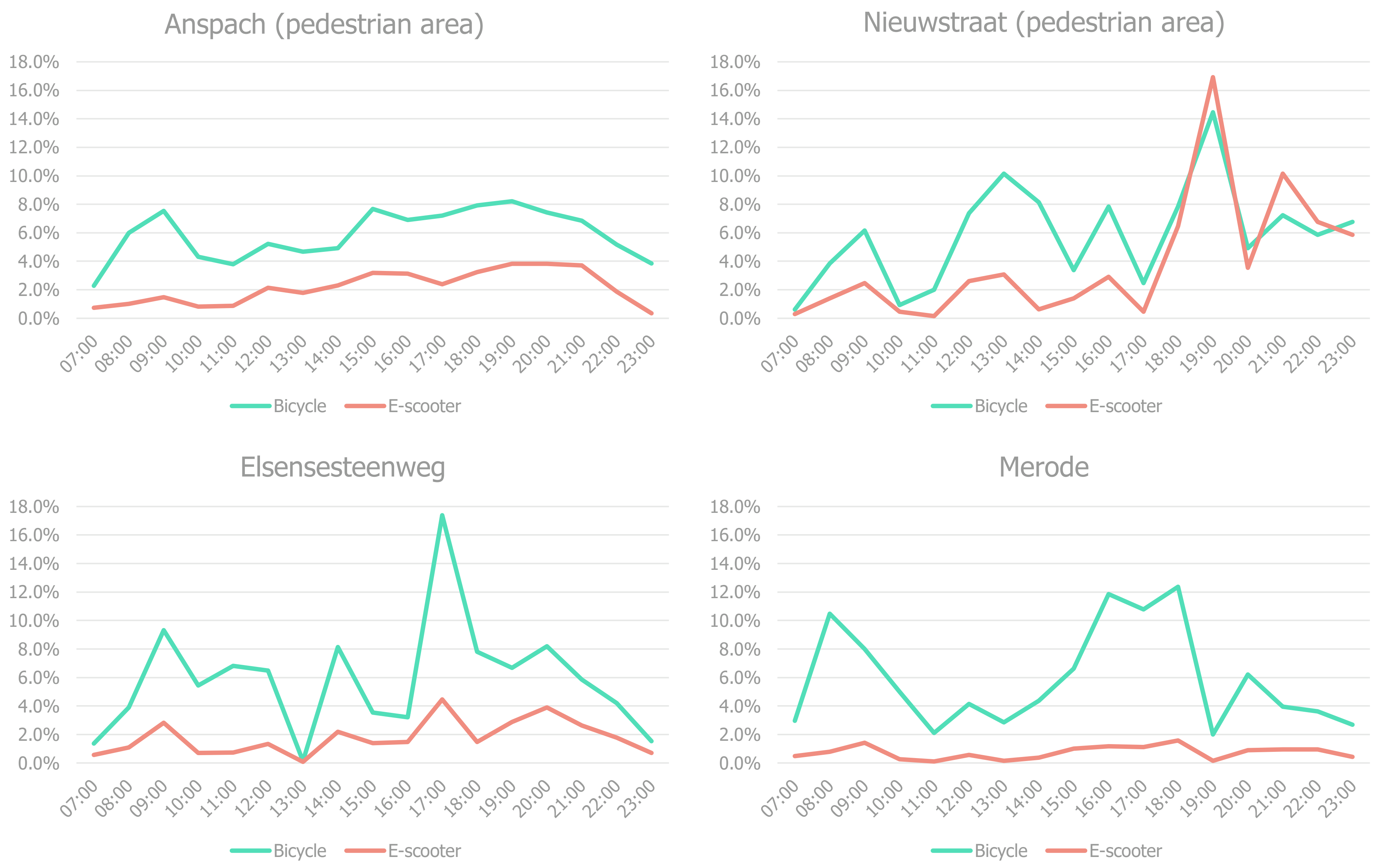


Figure 45: Distribution of cyclists and e-scooter users throughout the day on each of the four test locations

Subsequently, e-scooter users were studied in more detail. Here, the ratio between shared and private motorised e-scooters was determined, as well as the portion of non-motorised kick scooters. For this, a sample of 10 video hours was taken on each site divided between different hours and days of the week to keep a representative distribution throughout the observation period.

The share of shared e-scooters on the four test locations was also determined. This was done, based on manual observations of the camera images, where an e-scooter was classified as a shared e-scooter based on the colourful options and geometry. Figure 46 shows that, out of the 2.339 observed e-scooter users, the largest portion of e-scooter users were using a shared e-scooter (i.e. between 77% and 85.3%), followed by private e-scooters (11% to 20.9%). Regular non-motorised kick-scooters were only marginally present. This seems to contradict the findings of the questionnaire, in which it was found that private e-scooters have a high share. However, given the specific nature of this observation (i.e. crowded shared spaces in urban environments with readily available e-scooters), and absence of an influence of suburban and rural context, a higher share of shared devices was suspected, since a higher share of private e-scooters is expected to be observed in less dense environments.

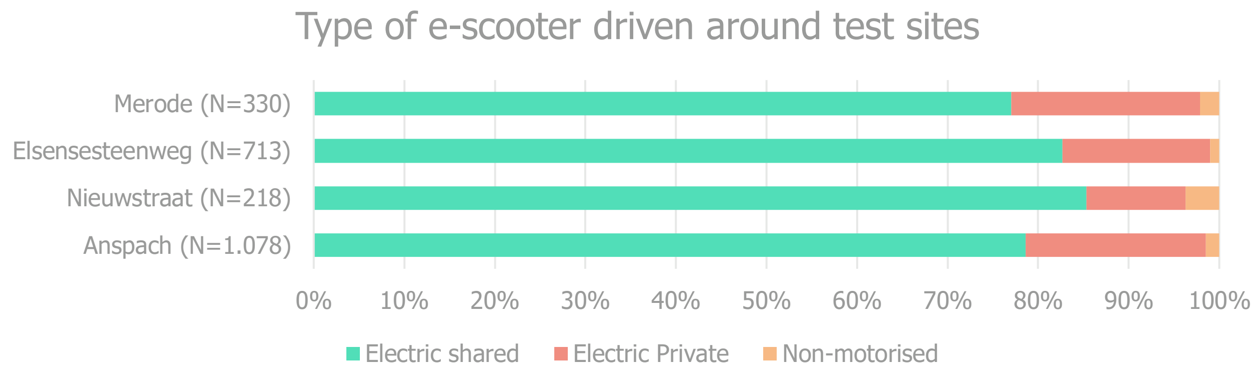


Figure 46: Portion of shared and private e-scooters on each test location

4.2.2 Ridden speeds and speeding infractions

A large part of the behavioural observation is focussed on speed and speeding incidences. This in order to better understand, not only the ridden speeds or speeding infractions with a speed limit of 25km/h, but more importantly speed compliance in pedestrian zones where lower speeds are obligatory (i.e. walking pace) or requested based on the local conditions (e.g. at very busy hours choose to adapt the speed). In order to get a more accurate insight in these driven speeds and speeding infractions, different locations are studied separately.

In the pedestrian areas of Anspachlaan and Nieuwstraat, a speed limit of 8km/h was taken for both cyclists and e-scooter users, due to larger anomalies in speed determination at very slow speeds. Therefore a little margin over walking pace was taken (i.e. around 5-6km/h) to account for little inaccuracies in speed determination based on the camera footage, as well as the difficulty of interpreting which speed can now be seen as walking pace. The results are shown in figure 47.

It can be observed that for Anspachlaan the ridden speeds of cyclists and e-scooter users are roughly the same with most of the users complying to the speed limit. However, quite some users disregarded the speed limit up to a speed of 21km/h.

For Nieuwstraat however, a different distribution can be seen. While quite some cyclists sticked to the legal speed limit of walking pace, e-scooter users seem to comply less often tot this speed limit, showing a more even distribution across all speeds up to 20km/h. Cyclists as well tend to disregard the speed limit, but to a lesser extent. Here differences between e-scooter users and cyclists are more pronounced compared to Anspachlaan, even though they are both pedestrian areas.

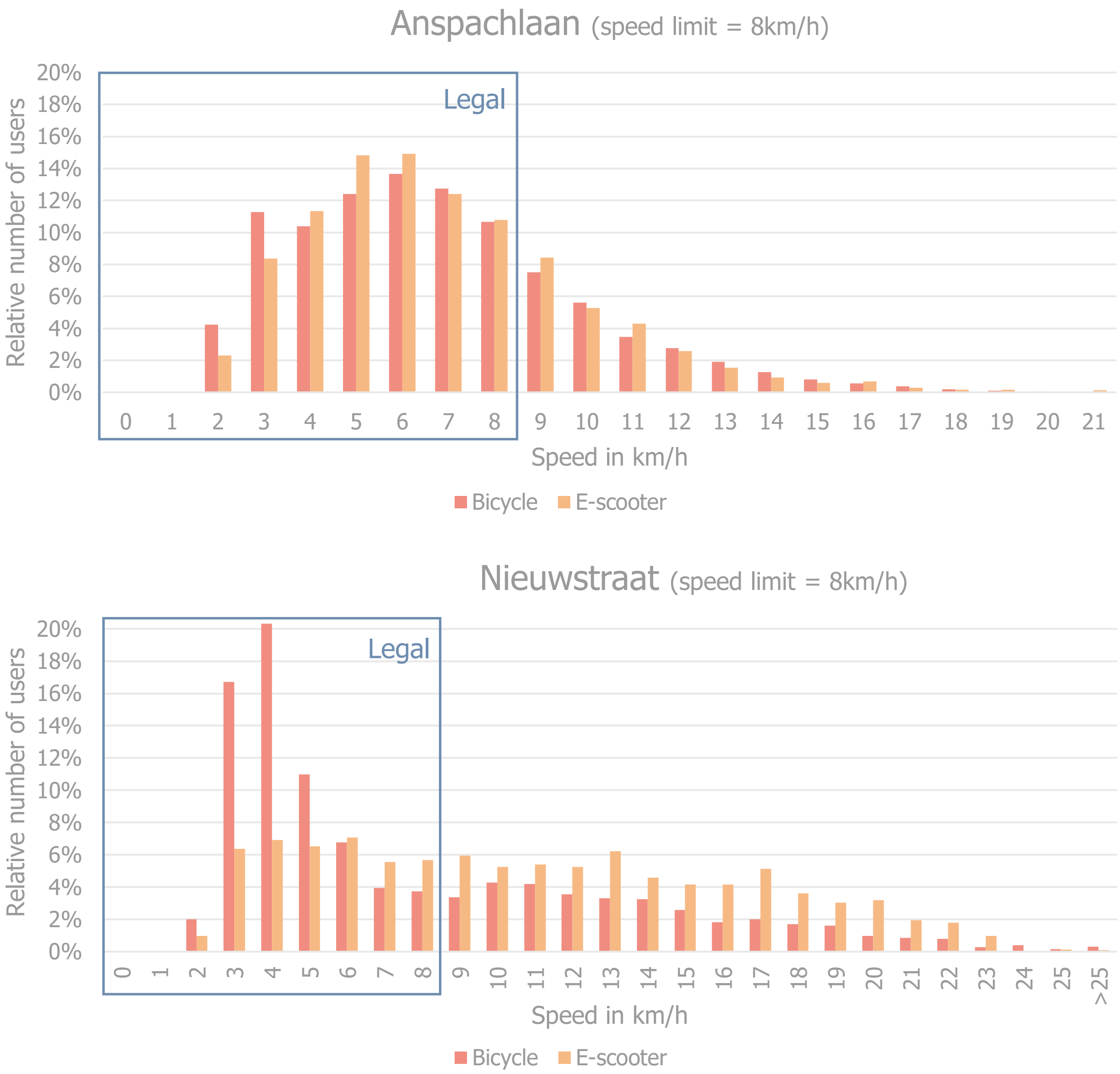
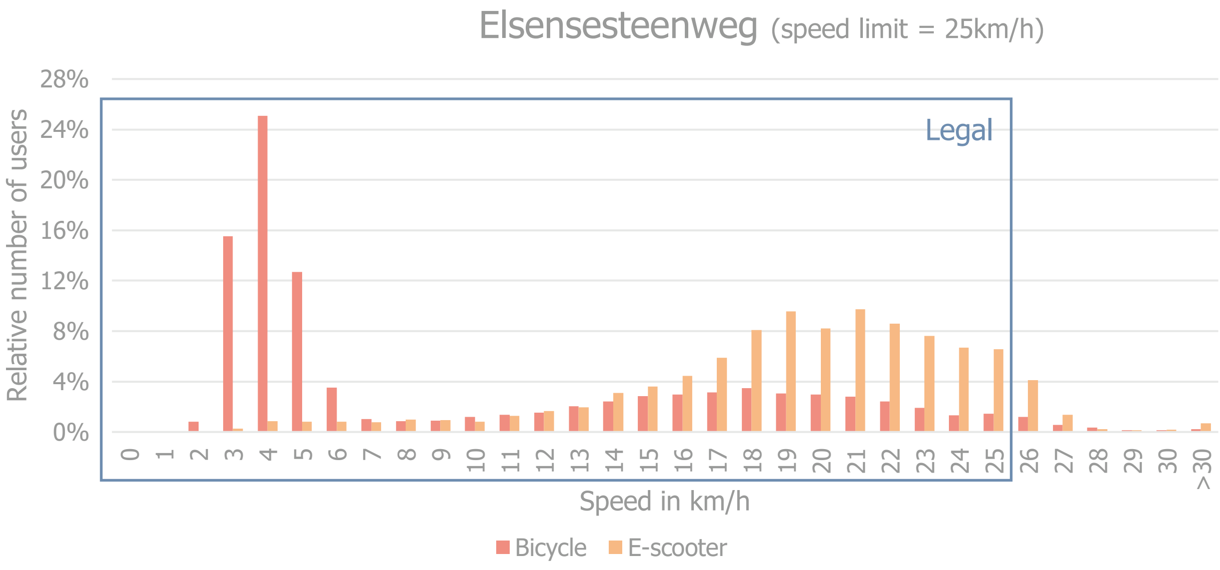


Figure 47: Ridden speeds by cyclists and e-scooter users in the pedestrian areas of Anspachlaan and Nieuwstraat

In the other shared spaces, a legal speed limit of 25km/h applied. Since legally compliant e-scooters and e-bikes need to have a maximum speed of 25km/h, and cycling faster than 25km/h with a conventional bicycle is physically challenging, it is to be expected that this speed limit of 25km/h won't be exceeded as often compared to the pedestrian areas. Here no speed determination anomaly was taken into account due to the better speed determination at higher speeds by the software. The results are shown in figure 48.

Indeed, it can be seen that the legal speed limit is not exceeded very often. While some users were registered to go faster than 25km/h it has to be stated that this is a minority, that even can be taken into the legal speed limit of possible camera abnormalities. In only a few cases ridden speeds higher than 28km/h could be observed possibly by non-legal scooters or sporty cyclists.

While the ridden speeds of cyclists and e-scooter users seem to be more or less equal at Merode, a more notable difference can be seen between cyclists and e-scooter users in the Elsensesteenweg. It seems that e-scooter users choose more often to stick to the maximum speed of their scooter, while cyclists tend to cycle much slower and show a more even distribution over all speeds. It seems that e-scooter users choose to ride at faster speeds, just because they 'easily' can (i.e. because fewer physical effort has to be exerted) compared to cyclists. In fact, it doesn't mean that if an e-scooter can reach a speed of 25km/h, it therefor has to be used at all times with these speeds. E-scooter users tend to show less often a ridden speed adapted to the situation.



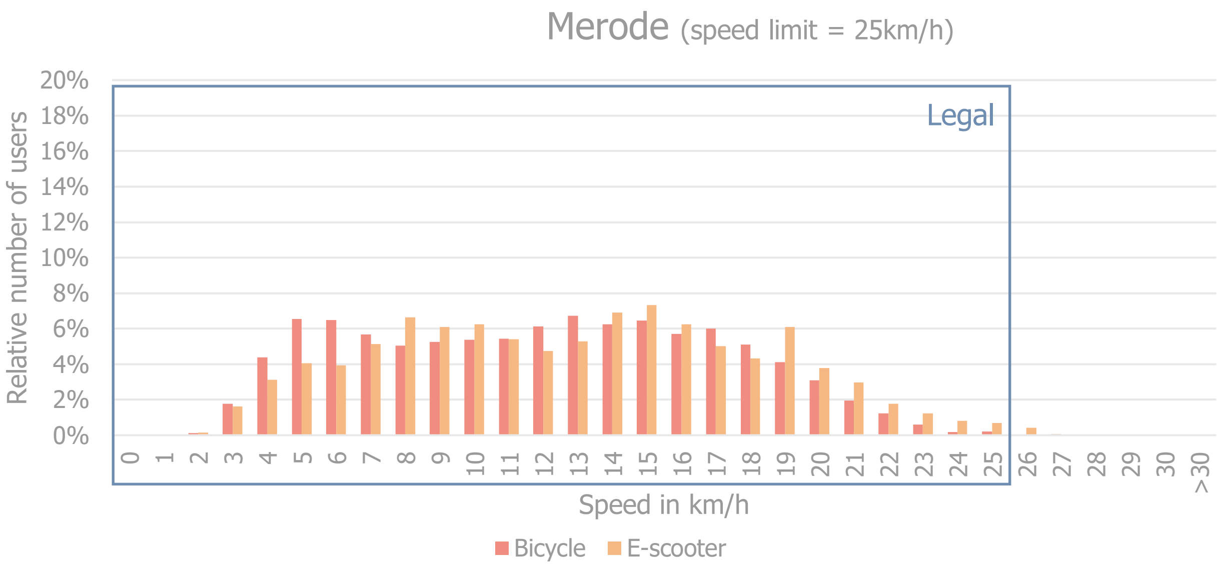


Figure 48: Ridden speeds by cyclists and e-scooter users in the shared spaces of Elsensesteenweg and Merode

When speed compliance is strictly taken into account, it can be stated than on average 14.3% of the road users were speeding at the time of these camera recordings. However, large differences can be observed between the pedestrian areas and regular shared spaces, as visible in figure 49. In the pedestrian areas of Anspach and Nieuwstraat respectively 29.8% and 45% of the cyclists and e-scooter users were speeding. In the shared spaces of Merode and Elsensesteenweg this only concerned respectively 0.3% and 4.6%. It therefore shows the importance of interpreting the aspect of speeding, dependent on the location.

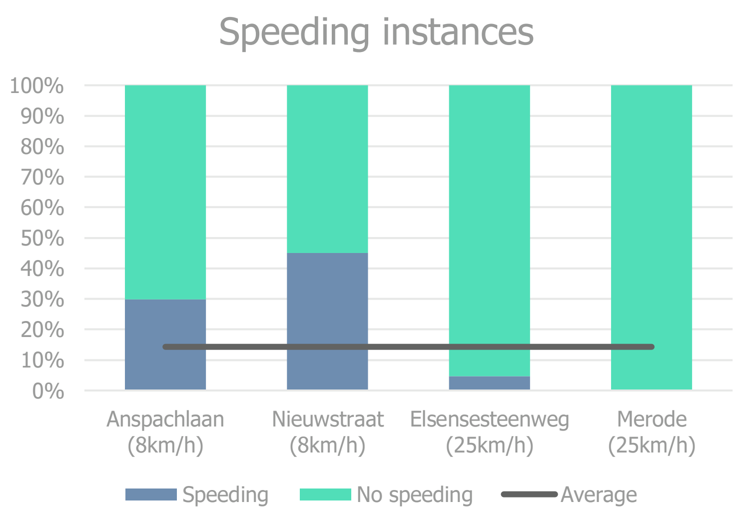


Figure 49: Speeding infractions per shared space for all users

institute

To further distinguish possible differences in speeding, a distribution of speeding infractions is made between the different locations, as well as the road users themselves in figure 50.

The speeding infraction data proves that e-scooter users tend to disobey the speed limit more often compared to cyclists. This is especially true in the pedestrian area of the Nieuwstraat where 63.6% of the e-scooter users made a speeding infraction compared to 37.3% of the cyclists (significant at the 95% confidence level). At the Anspachlaan no significant differences between cyclists and e-scooter users could be observed.

Also at the Elsensesteenweg a statistically significant difference could be observed in the speeding infractions, where e-scooter users disobeyed the speed limit of 25km/h more often compared to cyclists (i.e. 9.8% compared to 3.3%). It is possible that this relatively high figure, given the fact that e-scooters have to be limited to a speed of 25km/h, is due to a camera inconsistency. However, it remains striking that this is not present for cyclists. At Merode, no difference could be observed.

Since the difference in speeding infractions between cyclists and e-scooter users is mainly present at one location, namely Nieuwstraat, these results have to be interpreted with caution and cannot be generalised. However, as the distribution of ridden speeds already showed that e-scooter users speed more often or ride less often with a speed adapted to the situation, it can be claimed that speed compliance seems to be more often an issue with e-scooter users compared to cyclists. Furthermore.

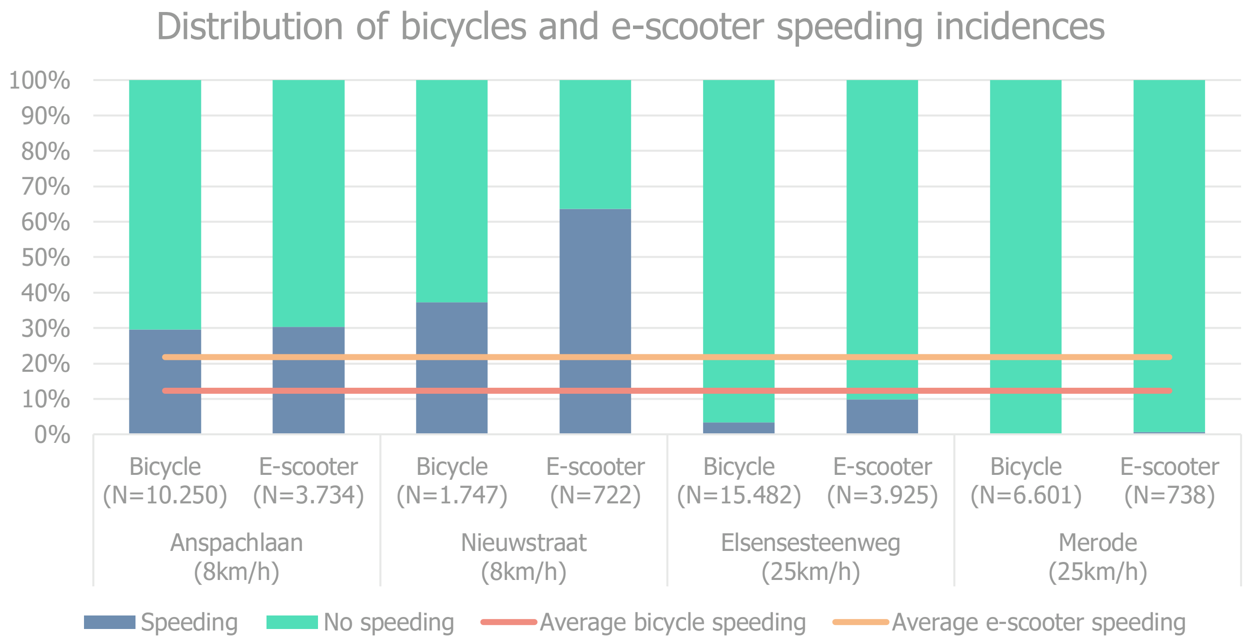


Figure 50: Distribution of the speeding infractions per road user and test location

When these speeding infractions are distributed over date and time, no day of the week effect could be observed. However, a time of day effect was found. The speeding data shows in figure 51 that most of the speeding infractions seem to take place during the night and morning. During noon and the evening lower infraction rates are observed. This can be explained by the calmer moments of the day at night and in the early morning (infraction rates were higher in the early morning from 6a.m. to 7.59a.m. compared to the later morning from 8a.m. to 11.59a.m.). These moments of the day are in general calmer in which it can be seen as absurd to stick to a speed limit of walking pace with nearly no pedestrians present. Proportionally the number of e-scooters didn’t differ from the number of cyclists on these moments.

Furthermore, during the night no difference between e-scooter users and cyclists could be observed, while for the other moments of the day a statistically significant difference was present, showing higher infraction rates for e-scooter users.

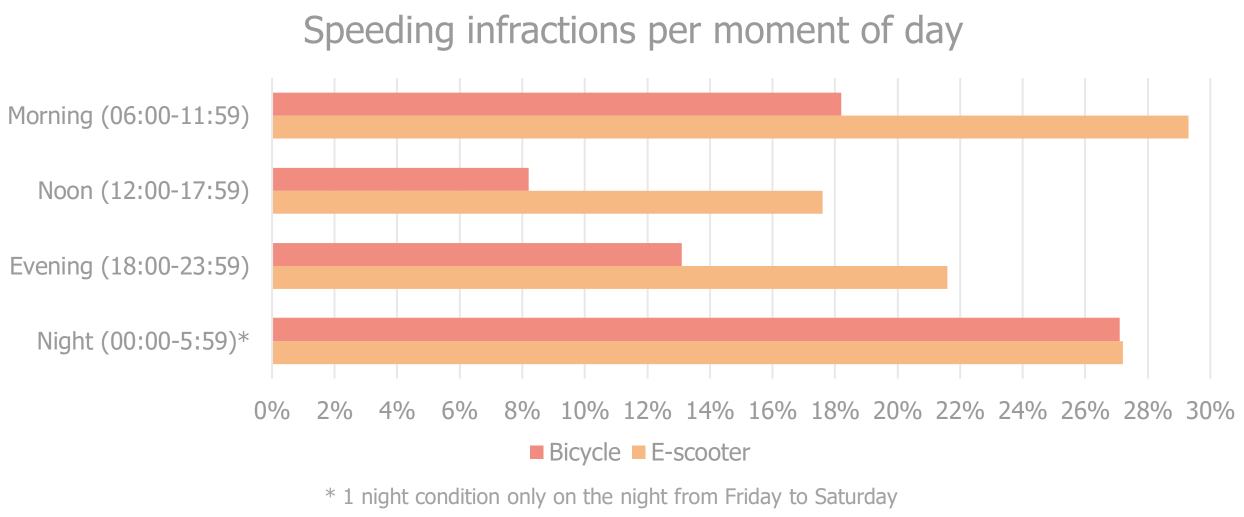


Figure 51: Speeding infractions per moment of day per road user

4.2.3 Riding with a passenger

Lastly, a specific focus was laid in the behavioural observation on riding with a passenger[7]. This behaviour, was evaluated for e-scooter users solely, by means of a manual coding of a sample of 10 video hours on each location. These video hours were divided between different hours and days of the week to keep a representative distribution throughout the observation period. The results are shown in figure 52.

Riding with a passenger was found to occur on average in 8.5% of the cases, with some differences between the locations. In only a very limited number of cases, more than 2 people were present on the same e-scooter. Using an e-scooter with a passenger was found to statistically significantly differ between users of shared and private e-scooters. Riding with a passenger occurred almost exclusively on shared e-scooters, compared to private e-scooters, where the behaviour was practically absent.

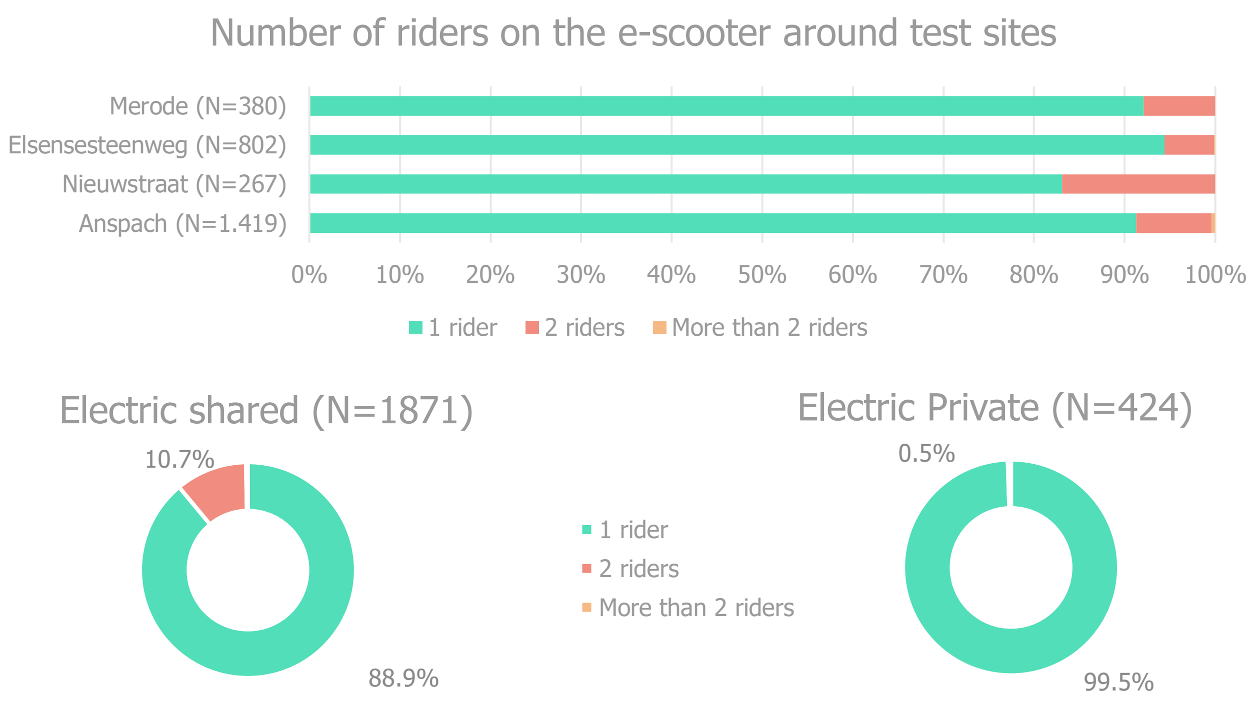


Figure 52: Proportion of riding with a passenger per location and per type of e-scooter for all locations

[7] At the time of the measurement, riding with a passenger was still legally allowed. As from July 1st 2022, the Belgian government decided to prohibit this behaviour.

Figure 53: Use of a shared e-scooter with a passenger while holding hands with a pedestrian

Figure 54: Use of a shared e-scooter with 2 passengers (three users on one e-scooter)

4.3 Conflict analyses

4.3.1 Overview of interactions and conflicts

For the conflict observation, the four different sites were again examined. First an overview is given in table 14 of the total number of observed road users, interactions, and conflicts with the following specifications:

- Road users (incl. pedestrians): all counted vulnerable road users (i.e. pedestrians, cyclists, and e-scooter users)
- Interactions with bicycle or e-scooter users: the number of interactions in which at least one cyclist or e-scooter user was involved. This is based on a Safety Performance Indicator (SPI) lower than 4.5 seconds determined by automatic conflict software (it is expected that road users did not influence each other if a value higher than 4.5 seconds is observed)
- Conflicts: Conflicts determined by the software based on TTC< 1.5 seconds and PET < 1 second

Table 14: Overview of number of vulnerable road users, interactions and conflicts on the tested locations

Location	Road users (incl. pedestrians)	Interactions with bicycle or e-scooter	Conflicts
Anspach (8km/h)	185.330	22.685	2.173
Nieuwstraat (8km/h)	108.303	2.252	180
Elsensesteenweg (25km/h)	79.136	2.470	233
Merode (25km/h)	18.006	625	52
Total	390.775	28.032	2.638

4.3.2 Number of interactions

When the number of interactions (solely determined based on the SPI value of 4.5 seconds) are taken into account, the distribution of these interactions over the different locations is shown in figure 55. Data shows that most interactions took place at Anspach, accounting for 81% of all observed interactions, after which respectively the Elsensesteenweg (9%), Nieuwstraat (8%), and Merode (2%) follow. This means that 88.5% of the interactions were observed in pedestrian areas, while only 11.5% of the interactions took place in the regular shared space. This is no surprise, given the higher number of pedestrians present in these pedestrian areas. Most interactions took place with cyclists, which is logical, given the higher number of cyclists present on each location.

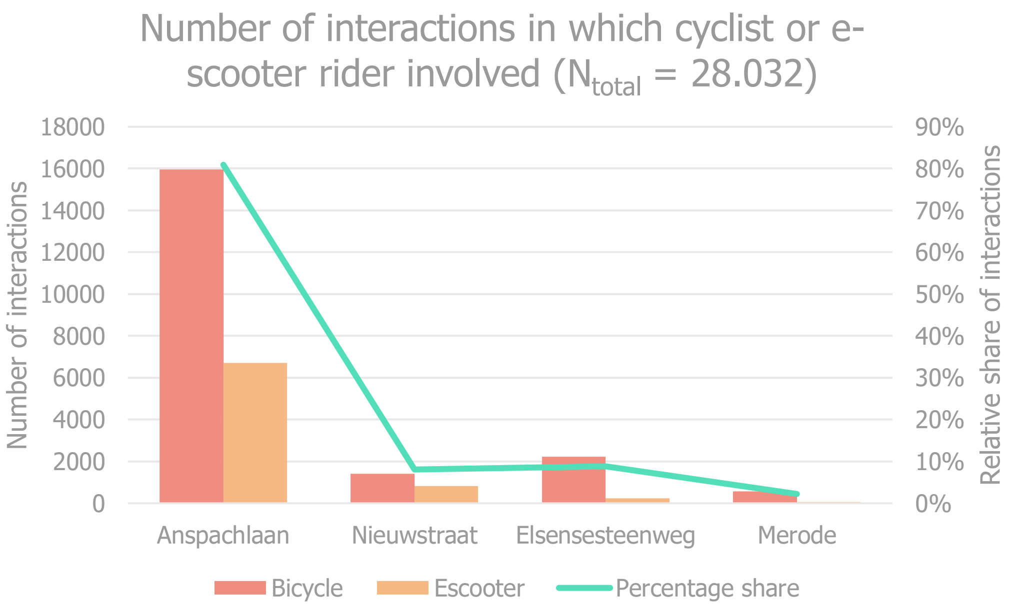


Figure 55: Number of interactions observed per test location in which a cyclist or e-scooter riders was involved

When the number of interactions with a bicycle or e-scooter user is related to the number of cyclists and e-scooter users (thus pedestrians excluded), it shows a difference between the pedestrian areas and regular shared spaces (figure 56). In pedestrian areas, an equal number or even more interactions take place than cyclists or e-scooters counted, compared to the other shared spaces. This can be explained by the high number of pedestrians present, where one cyclists or e-scooter user can have multiple interactions. At Merode and the Elsensesteenweg more free flow situations (situation in which road users didn't influence each other) were present.

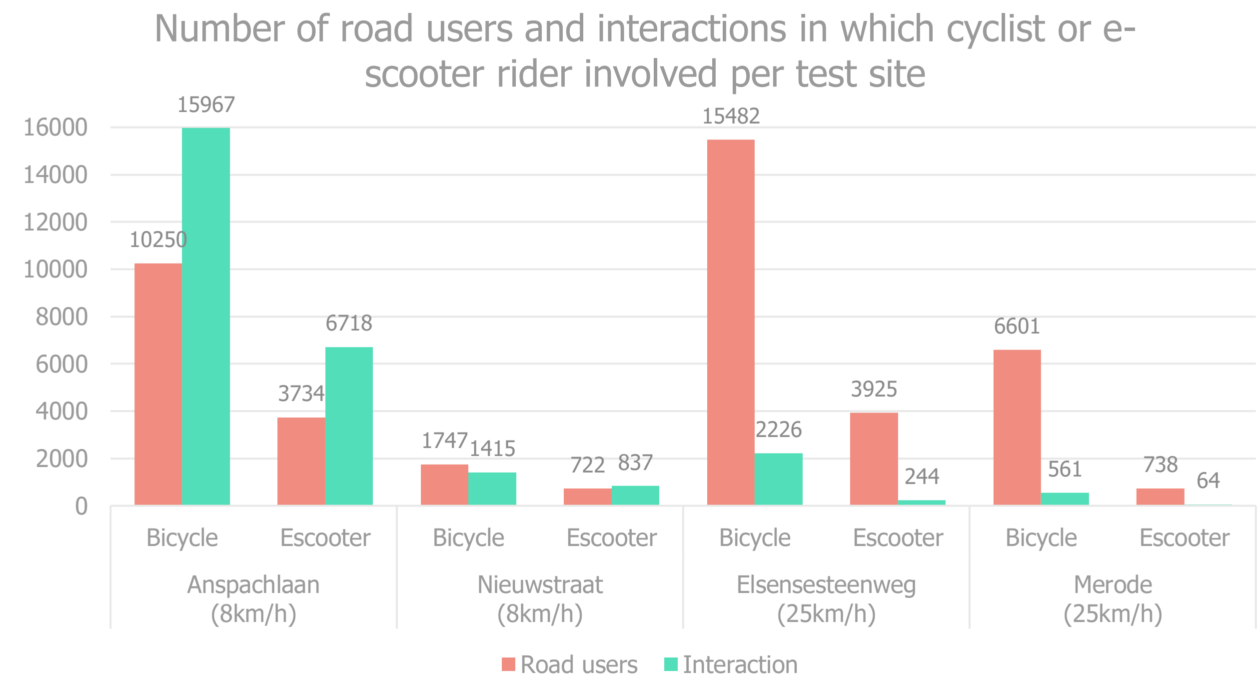


Figure 56: Number of road users and interactions observed per test site

4.3.3 Number of conflicts

Subsequently, conflicts are studied, and the conflict rate is determined. Based on the conflict data, 93.0 conflicts per 1.000 interactions could be observed with cyclists, while for e-scooters this comprised 96.9 conflicts per 1.000 interactions. This conflict risk based on the number of interactions was found not to be significantly different (p = 0.315607). Bicycle and e-scooter users equally often get involved in a conflict in relation to the number of interactions.

However, when the conflict risk was determined based on the number of cyclists and e-scooters it is shown that 55.0 conflicts per 1.000 cyclists could be observed, while for e-scooters 83.6 conflicts per 1.000 e-scooter users were found. This difference was found to be statistically significant (p<0.00001). This shows that e-scooter users more often get involved in a conflict, compared to cyclists, if it is calculated over their user counts. This effect is visible in figure 57.

An overview per test location is also given in figure 58.

So, if a cyclist or e-scooter encounters another vulnerable road user, it is equally likely to result in a conflict, based on the number of interactions. But in general, an e-scooter rider encounters more interactions and thus more conflicts than a cyclist.

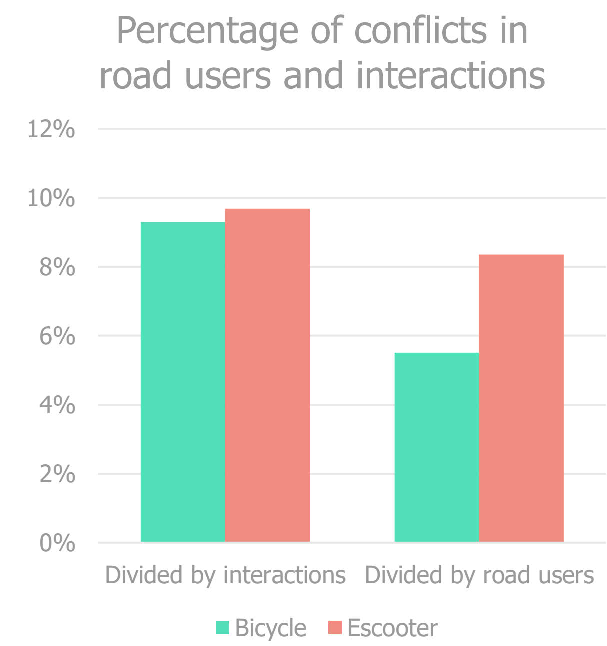


Figure 57: Conflict rate for cyclists and e-scooter users

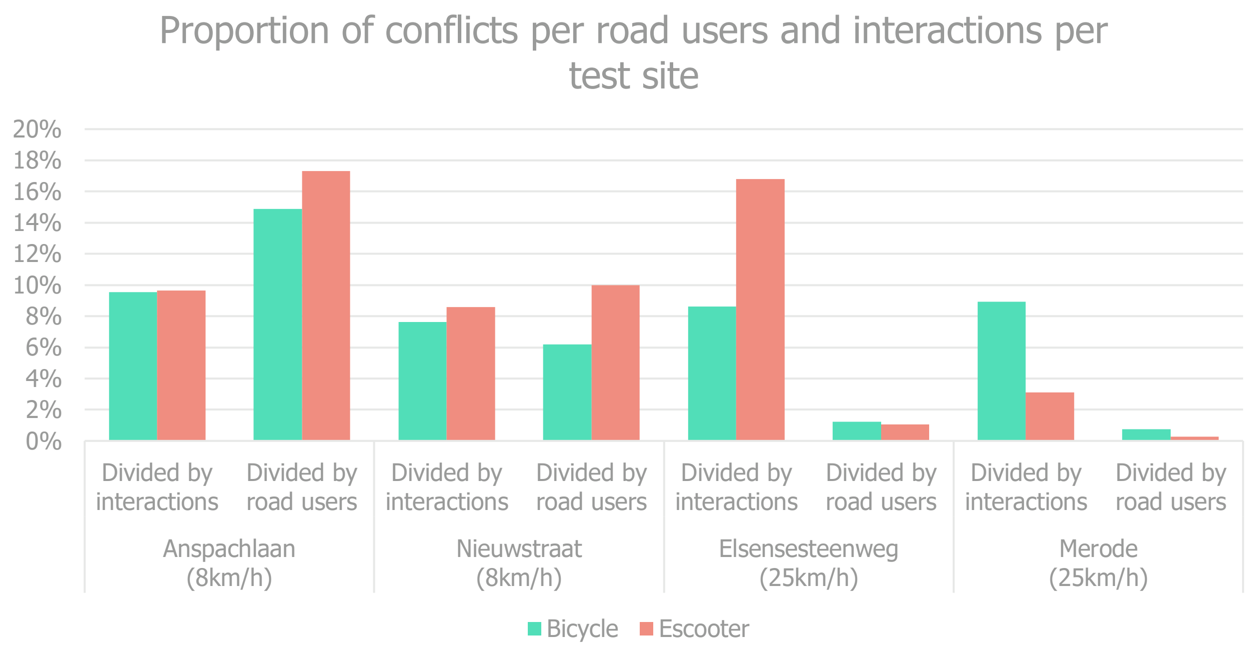


Figure 58: Conflict rate for cyclists and e-scooter users per location

This shows that e-scooter users have a higher conflict risk than cyclists in terms of the number of users, but not over the number of interactions. However, large differences between test-sites could be observed.

4.3.4 Insight in conflicts

4.3.4.1 Insights based on total number of conflicts

Conflicts occur between multiple road users. In the shared spaces researched, the main focus was laid on vulnerable road users. Figure 59 gives an overview of the road users between which the conflict took place. It largely shows that conflicts, in which a bicycle or e-scooter was involved, mainly occur with other pedestrians conflicts between other bicycles or e-scooters are quite scarce. Since a large difference was present in the number of conflicts between bicycles and e-scooters, a statistical test was performed, which shows that no significant difference is present between e-scooters and bicycles. They get involved equally often in a conflict with a pedestrian. The higher share of conflicts with a pedestrian and a bicycle can thus largely be explained by the exposure effect (i.e. more cyclists present).

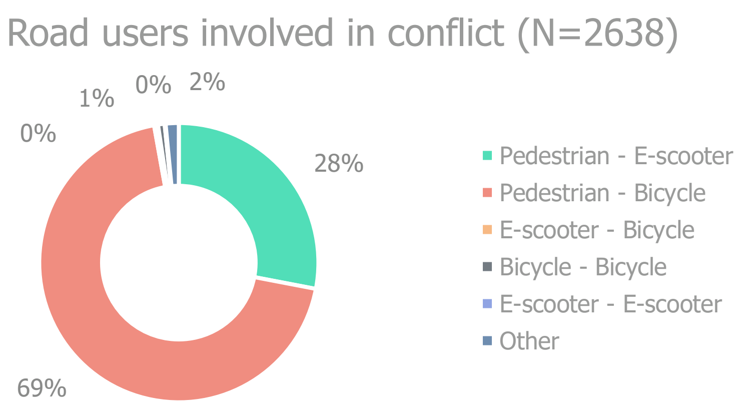


Figure 59: Road users between which the conflict took place

Speed compliance at the time of the conflict was also researched. Figure 60 shows that in 1 out of 4 conflicts, the conflict was preceded by a speeding infraction (i.e. speed >8km/h in pedestrian zones and >25km/h in regular shared spaces). While this does not explain the cause of the conflict, it can be stated that speed could have played a role in these conflicts to occur. In fact, this speeding issue is more often present in pedestrian areas as found before. To add, no statistical difference could be observed between cyclists and e-scooter users (p=0.583). Here, it was not possible to check for inappropriate speed to the situation (e.g. riding at 20km/h in a 25km/h speed zone, while a speed of 15km/h would be more suitable to a busier situation)

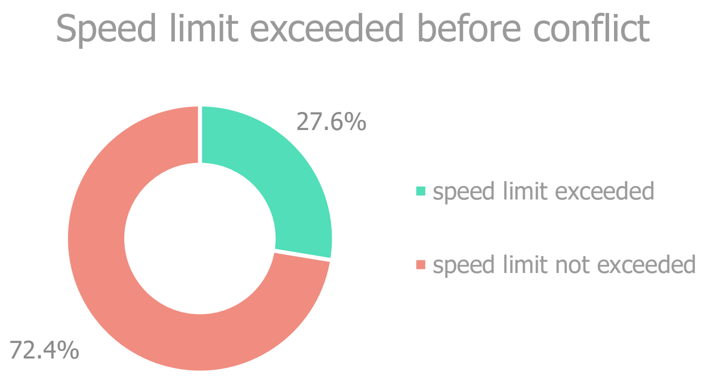


Figure 60: Speed compliance at the time of a conflict

4.3.4.2 Insights based on a small manual selection of conflicts

Further insights were generated based on a small manual selected sample of conflicts, for which the videos were rewatched. Multiple variables were coded and analysed. The following factors were coded: the type of road user involved in the conflict, the road user that was believed to cause the conflict, the general cause of the conflict based on personal interpretation, the type of conflict (direction of travel of the road users), and some demographic variables. A distinction between the locations was not made due to the low conflict counts on some locations. Furthermore, no distinction was made between the proportion of shared or private e-scooters given the relatively low number of conflicts and high share of shared e-scooter users observed on the locations (possibly overrepresented in terms of exposure).

Firstly, it can be observed in figure 61 that the vast majority of the manual selected conflicts happen with a pedestrian. In 84% of the conflicts a pedestrian was involved (i.e. 40% of the conflicts happened between an e-scooter user and pedestrian, while 44% happened between a cyclists and pedestrian), while in 16% of the conflicts an interaction took place between two cyclists, a cyclist and e-scooter user, or a non-vulnerable road user. This is not surprising given that large proportion of pedestrians present in these shared spaces. This finding is also confirming the previous finding in 4.3.4.1. where conflicts with pedestrians were found to happen in most of the case.

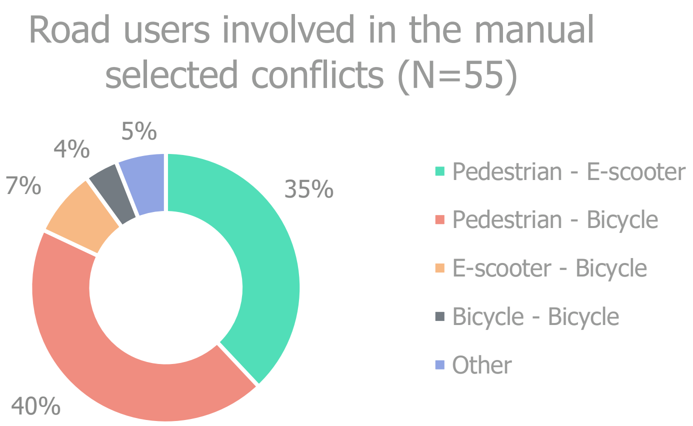


Figure 61: Road users that were involved in the verified conflicts

Secondly, it was studied, based on own interpretation of the conflict videos, who could be seen as the main causer of the conflict (figure 62). In 40% of the cases the e-scooter user was the main causer of the conflict; likewise, in 40% of the cases the cyclist was the causer. But also in 15% of the conflicts, a pedestrian caused the conflict. Only in 6% of the conflicts, both parties commonly caused the conflict.

Important causes for these conflicts, as shown in figure 63, were inappropriate speed, not following the priority rules or having some kind of miscommunication, distraction, or other causes. Differences between bicycles and e-scooters were not statistically significant.

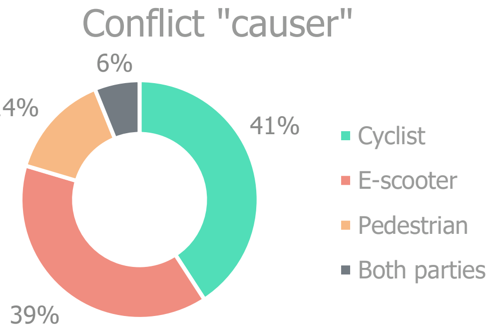


Figure 62: Main party "causing" the conflict

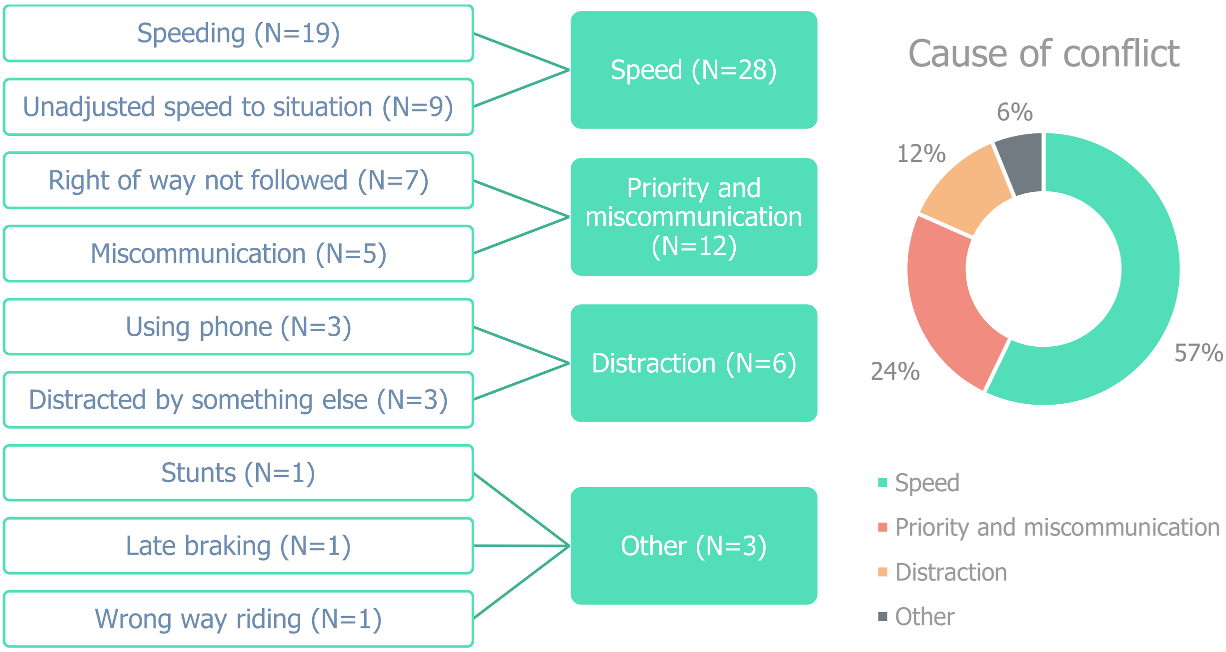


Figure 63: Conflict causations

In 6 of the 26 conflicts in which an e-scooter was involved, the e-scooter was occupied by 2 riders (while this was not the cause of the conflict to happen). In 4 out of these 6 conflicts with a passenger on the e-scooter, speed was the main cause of the conflict.

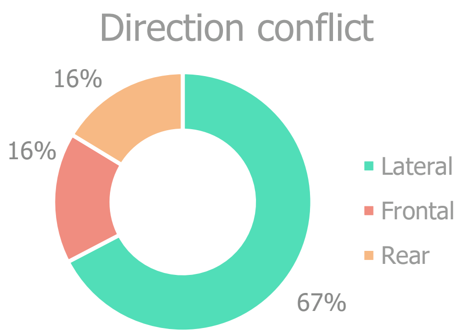


Figure 64: Direction in which the conflict occurred

Furthermore, it could be observed that most of the conflicts happened laterally. Only in 1 out of 3 conflicts the road users were having a frontal or rear conflict. For this, no significant difference between the road users was observed.

No differences were found in the conflict speed between cyclists and e-scooter users when they caused the conflict, even though it was shown that e-scooter users tend to ride more often with higher speeds. However, when pedestrians caused the conflict, it could be observed that the conflict speed of e-scooter and bicycle users was lower compared to cases in which the pedestrian did not cause the conflict.

Lastly, it was observed that more men had a conflict compared to women, both for bicycles and e-scooter conflicts. However it has to be noted that a likelihood exists that e-scooter users are more dominated by a male population and that more male cyclists possibly crossed the different testing locations. Since the gender of all passing road users couldn't be determined (i.e. exposure), a claim of a gender effect has to be made with caution and further research is needed.

4.4 Crashes

4.4.1 Methodology

Crash involvement was investigated through self-reported crashes and near-crashes, gathered via the survey in users of the different transport modes (e-scooter, bicycle, e-bike). In this case, all users were considered, even if the transport mode was used only once or in the past (i.e. only respondents that indicated to never use one of these modes weren't able to fill in the crash section of the questionnaire). This way, a larger dataset could be achieved. The crashes and near-crashes were investigated in relation to the number of users, but were not limited within a specific time period (i.e. crashes and near-crashes were not asked over a period of the past 2 years for example). Ideally these crashes have to be checked with exposure (i.e. how long someone is already using the transport mode, or the number of kilometres travelled with the transport modes on an annual basis). However, this exposure was not taken into account in the questionnaire.

4.4.2 Results

In total, 1 user out of 3 of the different transport modes has been involved in a crash, based on this self-reported crash data. It was shown that users of conventional bicycles were proportionally more often involved in a crash (i.e. 2 out of 5 cyclists have been involved in a crash). E-bike users on the other hand showed the lowest involvement in crashes (i.e. 1 out of 5 e-bike users have been involved in a crash). E-scooter users were found close to the average. It tends to show that cyclists are more often involved in a crash, compared to e-scooter users, while e-bike users are less involved in crashes based on this basic self-reported crash information. However, this says little about crash risk, since exposure has to be taken into account for this as well, which was not done in this questionnaire.

For near-crashes a different picture can be formed. Nearly 2 riders out of 5 of the different transport modes were involved in a near-crash. Here, it seems that e-bike users have a higher near-crash involvement (i.e. 45% was involved in a near-crash), compared to e-scooter users and regular cyclists. However, this difference was not significant.

It is not surprising that the crash involvement figures are higher for bicycles, since they are already much longer around as a transport mode, thus having a higher likelihood for a crash to happen (i.e. due to higher exposure). However, special attention is needed on the e-scooter crashes. Relative to e-bikes and conventional bicycles, e-scooters are not long around but are already showing a high crash involvement.

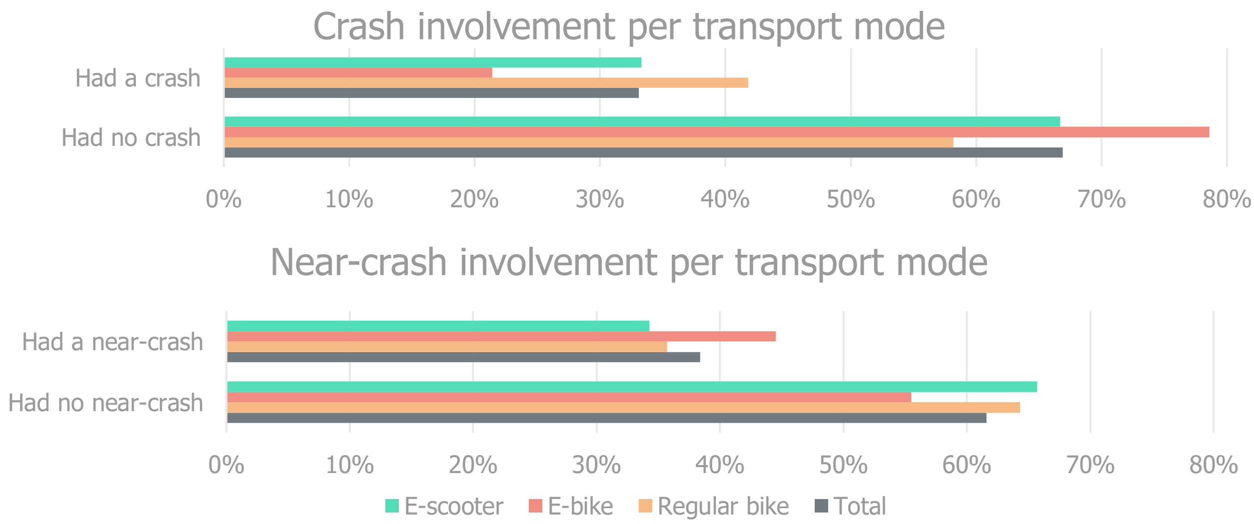


Figure 65: Crash and near-crash involvement per transport mode based on self-reported crashes

Further, the number of crashes and near-crashes that a single user can be involved in was investigated. This data shows that a large portion was only involved once in a crash or near-crash. However, the involvement of the same person in multiple (near-) crashes is not uncommon.

On average, 45.7% of all users that were involved in a crash, were involved in 1 crash, while 54.3% was involved in multiple crashes. Users of conventional bicycles are more often having multiple crashes, while e-bike users are more often involved once in a crash. For e-scooter users, a 50-50 distribution is found, where 50% was involved once in a crash and another 50% in multiple crashes.

For near-crashes the picture is more pronounced. 71.4% of the users that had a near-crash experience, have been involved in multiple near-crashes, while 28.6% only had 1 near-crash. This shows that near-crashes are quite common for these road users, not always resulting in a crash. Here, especially cyclists (both electric as regular) have a high share in multiple near-crash involvement. E-scooter users are again on a 50-50 distribution, were 50% was involved in a near-crash once, while the other 50% was involved in multiple near-crashes. This can potentially be explained by the fact that bicycles and e-bikes are much longer around in society compared to e-scooters, resulting in higher exposure and more possibilities of near-crash occurrences.

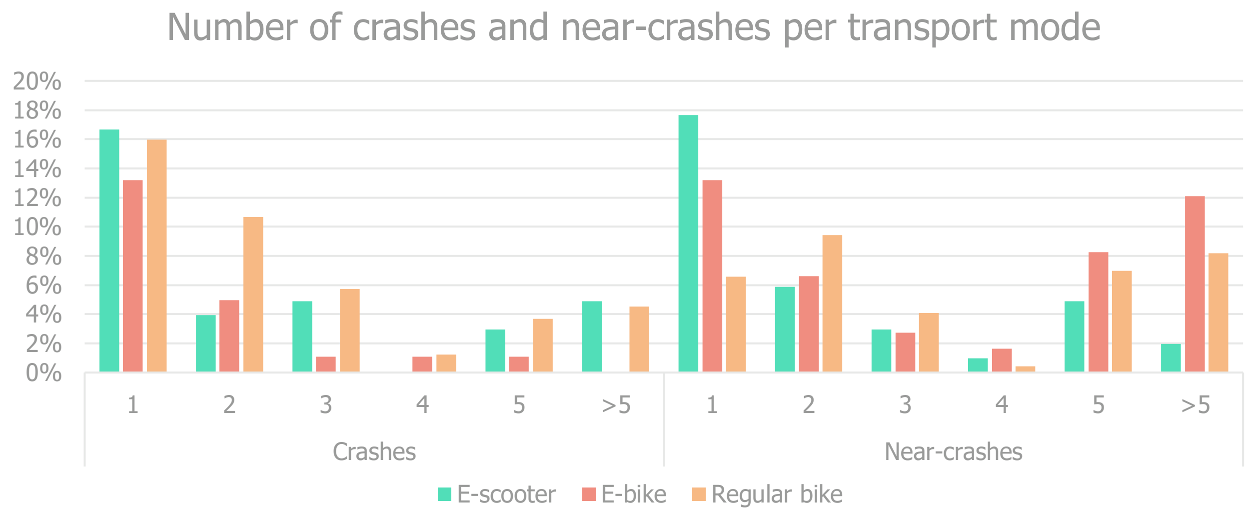


Figure 66: The involvement in multiple crashes and near-crashes per transport mode

Subsequently, insight is given in the type of crash in which these road users were involved, more specifically whether it concerns a unilateral (i.e. often due to a loss of control with no other road users involved) or multilateral (i.e. one or more road users additionally involved) crash. In total 326 crashes (i.e. 64 with e-scooters, 60 with e-bikes, and 202 with conventional bicycles) and 452 near-crashes (i.e. 63 with e-scooters, 183 with e-bikes, and 206 with conventional bicycles) were reported.

Unilateral crashes occur more often than multilateral crashes (i.e. 4 out of 5 crashes is unilateral, while 1 out of 5 is multilateral), and is present for all different transport modes. Here, a marginal significant difference can be found, showing a higher involvement of e-scooter users in multilateral crashes compared to the bicycle and e-bike users. Strikingly, this finding is the inverse of the PV analyses performed in (De Vos & Slootmans, 2023) where it was found that multilateral crashes were responsible for ¾ of the analysed crashes. This tends to prove the large underreporting of mainly unilateral crashes that is found in crash statistics, and which was also already found in the report of (Delhaye & Vandael Schreurs, 2022).

The causes of these unilateral crashes are quite diverse and different between the transport modes. E-scooter users indicate that in most of the cases, a technical problem caused the unilateral crash. Also, they admit that their own behaviour, as well as the weather conditions, played a role in the occurrence of the unilateral crash. Strangely enough, they also indicate that other road users have a cause in a unilateral accident. An explanation for this could be an evasive manoeuvre from the e-scooter rider, resulting in a fall, without hitting the other road user. Crash causes for e-scooters tends to differ from the PV analyses performed by De Vos & Slootmans (2023), where it was found that infrastructural problems had a high cause in unilateral crashes. It is possible that this crash causation in unilateral crashes is overrepresented in the PV analyses due to the fact that users want to blame the municipality for the bad infrastructure, while otherwise those crashes were maybe not present in the data. Furthermore, the way a person interprets the role of infrastructure in a crash can also play a role. Bicycle and e-bike users from our survey, on the other hand, blame the unilateral crashes largely on the road infrastructure, their own behaviour, and the weather conditions.

With the multilateral crashes, e-scooter users admit that it is quite often due to their own behaviour (i.e. in 37% of the cases), as well as the behaviour of the other road user (i.e. 32% of the cases). Weather conditions, road infrastructure, and technical problems do play a role, but to a lesser extent. Strikingly, bicycle and e-bike users indicate that in most of the cases, it is the fault of the other road user (i.e. 83% of the conventional cyclists and 55% of the e-bike users indicated that the crash was caused by the other road users). On the other hand, e-bike users also indicate that in 36% of the cases the crash was caused by a technical problem.

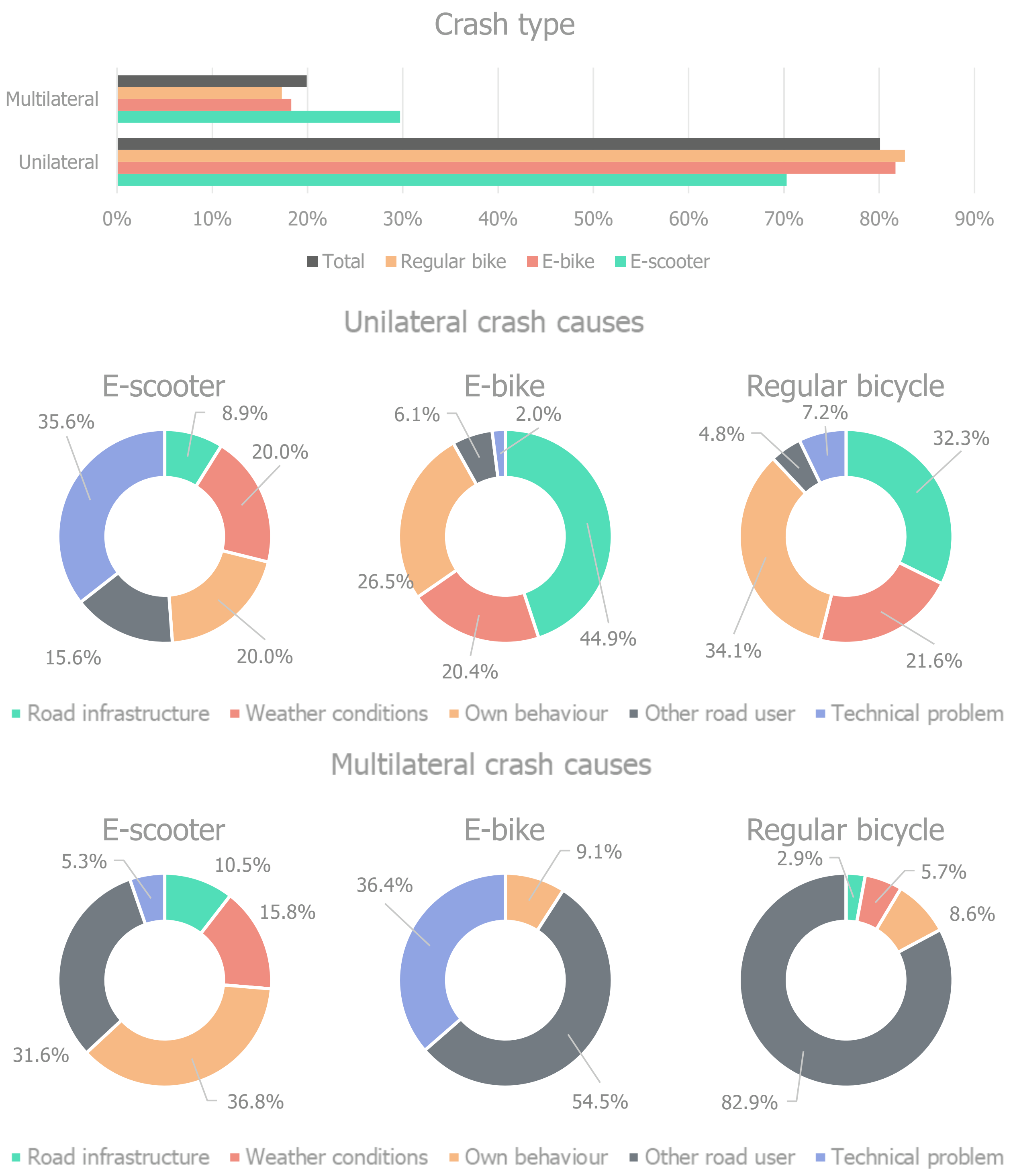


Figure 67: The share of unilateral and multilateral crashes and the causes for these crashes per transport mode

Looking at near-crashes, the distribution between unilateral and multilateral cases is different. With these near-crashes, 2 bicycle and e-bike users out of 3 indicate that the near-crash was multilateral, while for crashes this was only 20%. It seems to be reversely spread compared to the crashes. E-scooter riders on the other hand indicate that 55% of the near-crashes was multilateral, while 45% was unilateral. Bicycle and e-bike users thus have a higher involvement in multilateral near-crashes compared to e-scooter users.

The causes of these unilateral near-crashes are again quite diverse. Compared to the crashes, e-scooter users now indicate that technical problems are the least important factor in causing near-crashes. Their own behaviour is now most often indicated to cause a near-crash with e-scooter users, but weather conditions and road infrastructure are again playing a role. With conventional bicycle and e-bike users, the causes are more consistent with the crash analysis, indicating that a near-crash with a bicycle or e-bike is often caused by road infrastructure, weather conditions, and their own behaviour. Here, strangely, e-bike users indicate that the other road users also had a cause in the unilateral near-crash.

When comparing multilateral crashes and near-crashes, the biggest differences are seen. Here all users indicate that the other road user had the most blame in causing the near-crash. This was already the case with bicycles and e-bikes for crashes, but now e-scooter users are stating the same, indicating that it’s not their own behaviour anymore that mainly caused multilateral near-crashes.

Summarised, with regards to these crashes and near-crashes, road infrastructure and weather conditions are often claimed to play a role in unilateral crashes and near-crashes, while playing a minor role in multilateral crashes. Since these aspects go hand-in-hand, the road environment as a whole seems to play a large role for these road users. The same can be said about the own behaviour of the user, since the own behaviour also can lead to unilateral crashes with e-scooters, bicycles, and e-bikes. More information on these aspects is needed to get more insight into specific infrastructural problems, problematic weather conditions, as well as issues with the own behaviour leading to a crash. For this, further research is advised.

It seems that for e-scooters, technical problems with the e-scooter often result in a crash, while having a smaller impact on the occurance of a near-crash. This tends to indicate that a technical malfunction very likely leads to a crash, not leaving room for performing an action to avoid the accident. More insight in these technical malfunctions is advised, since they seem to lead to crashes directly. Further, it is often being indicated by cyclists (both e-bike and regular bike) and e-scooter users that the other road user has a big factor to play in a multilateral crash, while playing a more limited role in a unilateral crash. More insight into specific crash configurations is needed to be able to understand risky situations for these road users.

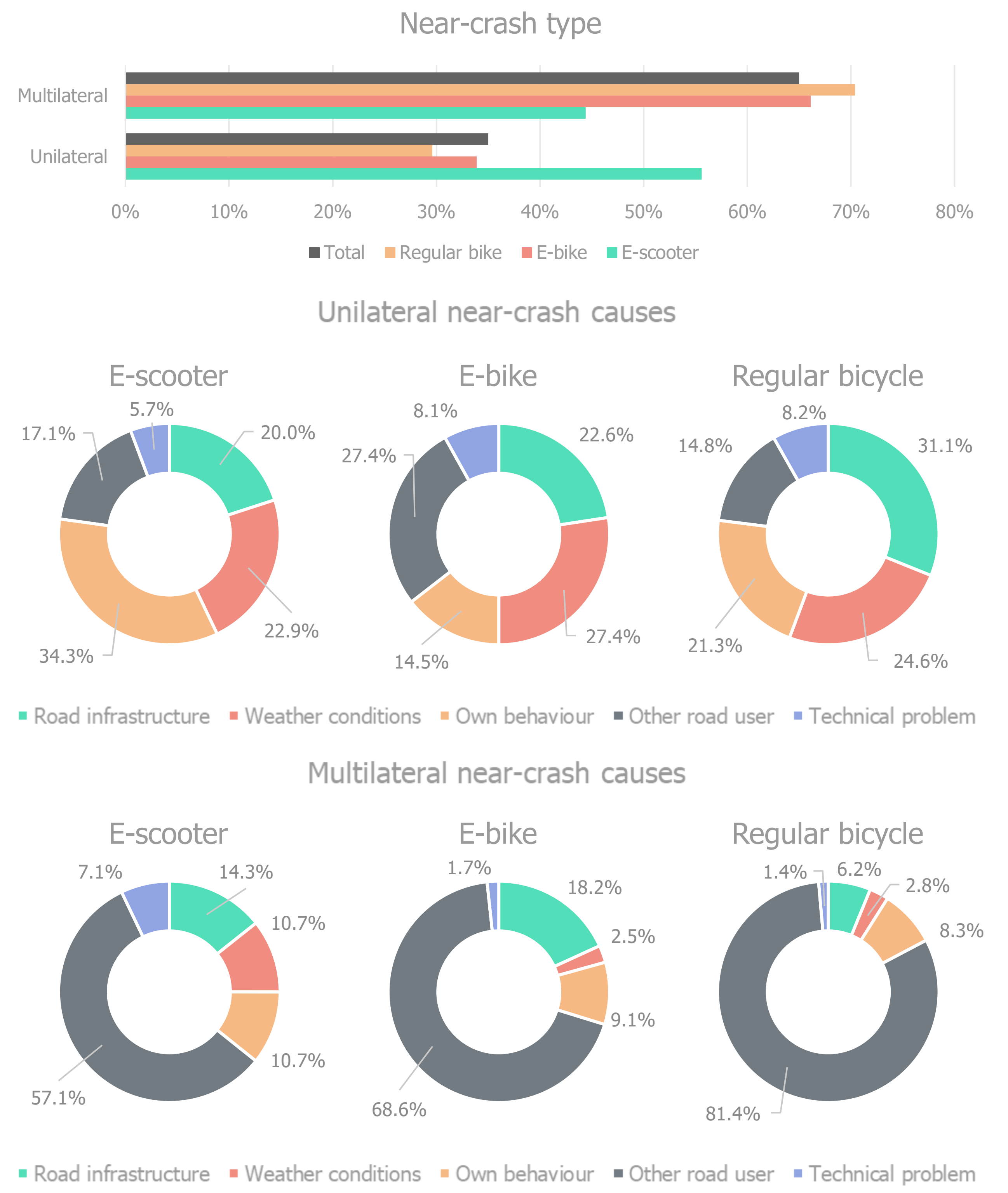
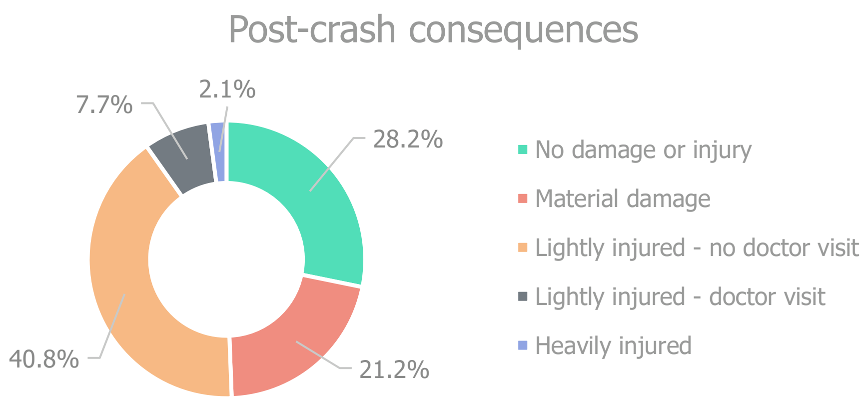


Figure 68: The share of unilateral and multilateral near-crashes and the causes for these near-crashes per transport mode

A large portion of crashes (i.e. 49.4%) only results into material damage or no injury or damage at all. It seems that this is slightly more the case for unilateral crashes compared to multilateral crashes, however, only a marginal statistical difference could be observed. Another large portion of crashes (i.e. 40.8%) only results in slight injury, for which no doctor or hospital visit is needed. Examples of these injuries could be some scratches, light bruises, lightly sprained ankle, etc. 9.8% of the crashes result in an injury fo r which medical attention is needed (which are more likely to be present in the PV-analyses report De Vos & Slootmans (2023). These injuries seem to occur more frequently with multilateral crashes, however the difference was only marginally significant. No statistical significant differences could be observed between the different transport modes.



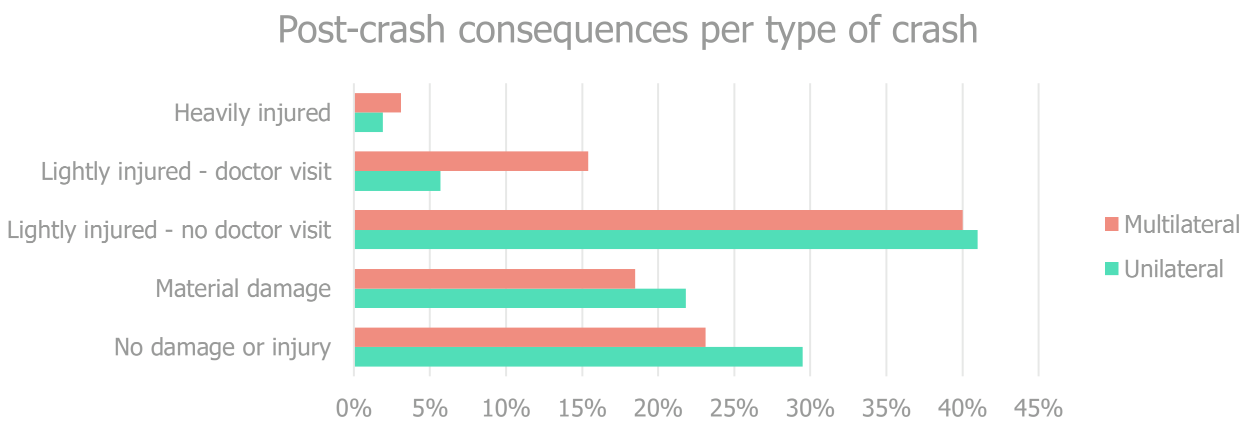


Figure 69: Consequences of the crash

It was already found that self-reported crashes are more often unilateral compared to multilateral. Further, the injury data showed that only a small portion of all self-reported crashes (i.e. 10%) resulted into a higher injury level, for which a doctor or hospital visit is needed. More severe crashes were slightly more often multilateral crashes, compared to unilateral crashes that had more often a less severe outcome. Therefor it has to be concluded that a very large portion of the uni- and multilateral crashes is probably underreported and not present in accident statistics, since crashes are often only reported with a higher injury level, or in multilateral crashes with a more severe outcome. Differences between transport modes were absent in crash outcomes, but were present in self-reported crash types and crash causes.

Some of these findings for e-scooter crashes are supported by recent hospital data research performed by Bjørnskau (2022) as well as experiences in other major cities (European Transport Safety Council, 2022). Indeed, it was found that the largest portion of e-scooter crashes were characterised by unilateral crashes, but multilateral crashes are also not uncommon. Causes for these crashes seem to differ, but can also be related to own behaviour, road infrastructure, and technical failures. Subsequently, Bjørnskau (2022) showed that only 8% of the crashes result in a serious injury, which is highly similar to the findings in this questionnaire study. Furthermore, Bjørnskau (2022) confirmed that many crashes were not recorded by the police, strengthening the assumption of a high underreporting rate of these crashes.

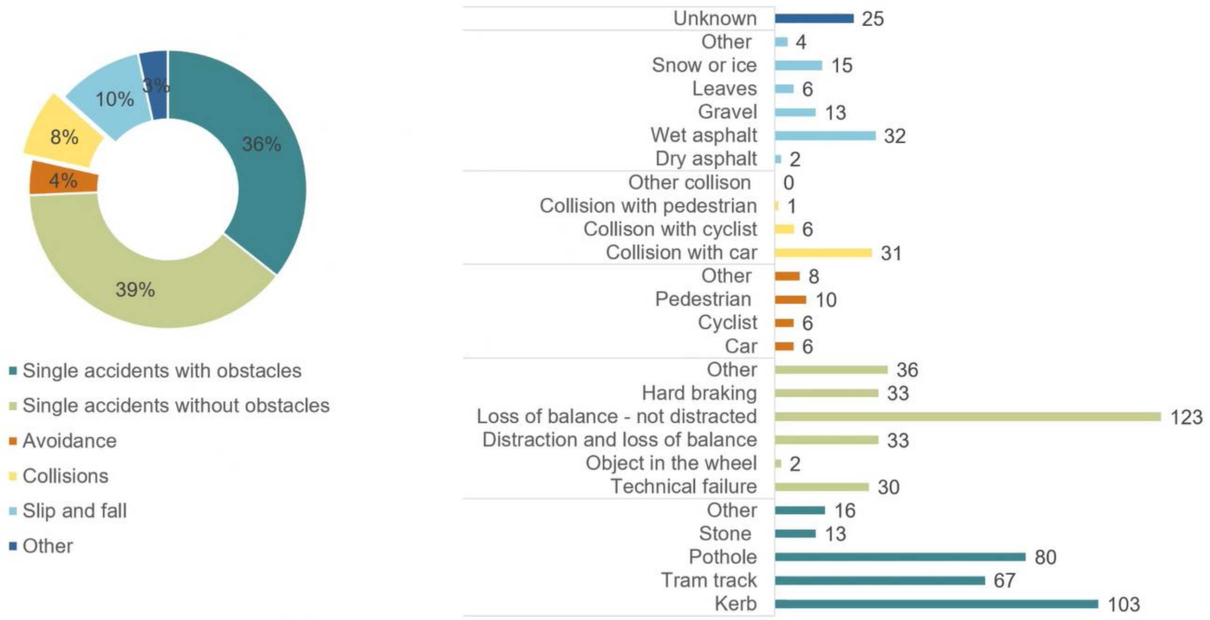


Figure 70: Hospital registered e-scooter crashes in Oslo 2019-2020 (Bjørnskau, 2022)

Bjørnskau (2022) further found that many crashes with e-scooters happened during weekend nights, as well as crashes as a result of alcohol intoxication. These characteristics seem to be a recurring factor (Vias institute, 2021). Crash research in Germany has for example shown that drunk driving, often as a result of rental e-scooters placed close to bars, is a recurring crash causation (European Transport Safety Council, 2022). Other crash causations that are seen in different cities comprise out of non-adapted speed, wrong use of the road, and loss of control. These are often a direct result of a lack of training, which can be essential due to the specific vehicle characteristics (e.g. small wheels, narrow handlebars, upright position, difficult to steer and keep balance, lights close to the road, toy-like, etc.) (European Transport Safety Council, 2022)

These findings are again proven by a recent Belgian study performed by Dr. Pierre Youatou Towo cited in (Dardenne, 2022). Of the 170 patients admitted in the hospital, and included in this study, crash information was collected. It showed that 58% of the crashes occurred between 6 p.m. and 7 a.m. of which 30% occurred between midnight and 7 a.m. In 85% of the cases, the crash could be categorised as unilateral. Furthermore, 30% of all the patients self-reported to be drunk (which suggests that even more of them were under the influence of alcohol at the time of the crash). Eleven of the 170 patients were wearing helmets (ten of them privately owned the scooter), and the most common injuries were head injuries and lower and upper limb dislocations. The more severe crashes were registered after 6 p.m. Lastly, based on a survey collected from those patients it was further found that in 75% of the crashes the e-scooter was rent from a shared provider.

5 Discussion

5.1 Categorisation and type approval

As mentioned in the introduction of this study, the field of PMDs is quite diverse. Given these different categorisations, different rules apply.

Micromobility devices, and some e-bikes (EPACS) have no type-approval as seen with the type-approved products via regulation 168/2013. They are, however, to some extent regulated in the EU by European standards (EN17128 for PLEVs and EN15195 for EPACs) and internationally through the standardization IEC TC 125. However, different countries apply different specific regulations concerning type-approval and legislative restrictions (European Transport Safety Council, 2022).

As an example, Germany was one of the first countries to raise concerns regarding the type approval and usage rules of e-scooters. Germany has put a light type-approval in place (PLEV ordinance) since mid-June 2019 in which e-scooters have the same rules as motorised vehicles, including a yearly renewable insurance linked with a small license plate (rules under evaluation until September 2023). Type approval rules are related to speed (max 20km/h + 10%, max power of 500W; two independent brakes, a bell, weight of the scooter). Other regulations that are put in place consist out of not allowing the use with a passenger, not riding side by side, not riding on the sidewalk, not riding in pedestrian zones, and no bags on handlebars (European Transport Safety Council, 2022).

In Belgium, type approval is not necessary for e-scooters and e-bikes that do not exceed a speed of 25km/h. E-scooters mainly have to comply to the EN17128 regulation or national legislation in the traffic code, such as: reflector use, presence of decent brakes, and the presence of a horn. Further, a new legislation on PMDs imposed on July 1st 2022 prohibits use with a passenger, riding on the sidewalk, and use by people younger than 16. Furthermore, parking is regulated to some extent. In general e-scooter users in Belgium are considered as cyclists when in motion (regardless of their speed), and have to adhere to their rules.

These different rules can cause ambiguity with users of PMDs. It can be worthwhile to revisit the categorisation and/or PMD standards, in order to clarify the matter for different users within Europe.

A limitation for this study is situated in this categorisation as well, since speed pedelecs were not filtered out of the PMD category, when conducting the questionnaire. However, due to their limited share in vehicle registrations, the impact is estimated to be low on the results.

5.2 Mobility

This study gives a necessary update on mobility information of PMDs, and more specifically e-scooters, e-bikes, and conventional bicycles. This information is quickly outdated due to the recent market boom, but has also been researched to a limited extent (especially for e-scooters). This study takes this a step further.

To start, one of the biggest differences from other studies was found with regards to e-scooters replacing walking and creating a modal shift from bicycles and public transport to the e-scooter (Brannigan et al., 2022; European Commission, 2021; Moreau et al., 2020). In fact, this study showed that e-scooters mainly impact car trips, have a slight positive impact on public transport use, and do not impact walking and cycling. Only e-bikes were found to impact public transport trips as well. This can be largely explained by the framework of this study, in which general effects and general use was questioned, contrary to other research where focus is laid on specific transport mode replacement on a trip level (e.g. ask for a specific trip which transport mode they otherwise would have taken). Therefor, direct comparisons with these studies cannot be made. However, this more general approach does lower the risk of coincidental transport mode replacement (e.g. took the car because someone needed to pick up errands) while taking deliberate choices more into account.

It were in fact deeper underlying psychological constructs, that gave more understanding in this transport mode choice. Higher order beliefs (e.g. contribution to society, positive impact on the environment, good feelings, health, etc.) were found to play the largest impact for choosing these transport modes, even higher than their utilitarian role (e.g. to meet friends, to go to the store, to go to work, to make multimodal journeys, etc.). E-bikes and bicycles even scored higher compared to e-scooters, where e-scooters showed a higher interest in use to impact the social norm (e.g. use it because it is trendy, to show social prestige, to impress others, etc.), which was also found to some extent by (Vias institute, 2021).

Next to that, mitigating factors could be identified that hinder the use of these transport modes. It was proven that motivational factors played the highest role in not selecting any of these transport modes (e.g. feelings towards safety, making plans to use the mode, not believing to contribute to environmental sustainability, automatically thinking of the car instead of these transport modes, etc.). Subsequently, the physical opportunity played a large role in not selecting the transport mode (e.g. a lack of time and money, not having the transport mode available as an option, not well-maintained devices available, etc.). This can also be proven by the questionnaire data that showed that a large portion of non-regular users has no access to a bicycle, e-bike or e-scooter, but also the lack of available space to safely store these devices seems to be an issue (especially at destinations and in more urban environments). Finally, the physical and psychological capabilities of a person had an impact on transport mode choice (e.g. not enough strength, not enough physique, not enough skills, not enough focus, etc.). Social support of others was less important. And even for bicycles, some of these factors were more relevant. The physical capabilities and automatic motivation hindered bicycle use even more compared to the other transport modes.

This shows that transport mode choice depends on multiple factors. E-scooters, e- bikes, and conventional bicycles have their own specific field of use and are not just replacing one another. While it is possible that e-scooters, e-bikes, and bicycles can be rivalling with each other for specific trips (e.g. an e-scooter is equally often used as a bicycle for first-last mile trips), the collective effect on the replacement of car trips, seems to be a more beneficial effect. It further shows that mode choice is a difficult to grasp concept, not solely leaning on derived demand anymore but taking much more aspects into consideration. This was made visible by the psychological models, and the simple fact that a conventional bicycle (or even multiple) is very frequently owned in the household, even by people that can be considered as non-regular users (i.e. those riding less often than on a weekly basis). Showing that just the fact of having access to a mode doesn't mean that it makes the person a regular user. In addition, a person who is using an e-scooter, isn't necessarily going to choose a bicycle if the e-scooter would be taken away (visible in the non-usage figures that just mainly showed higher car use). The same can be said about bicycle and e-bikes, showing specific reasons for taking the transport mode.

The role of physical activity cannot be ignored, since it was shown that all regular users of these PMDs were more physically active compared to their non-regular user equivalents. It is possible that this is a direct effect of the physical effort needed to propel these devices. The physical effort can be expressed as METs or metabolic equivalents of tasks. Previous studies have found higher MET values of 6.8 for conventional bicycles and 5 for e-bikes (Castro et al., 2019) compared to a value of 4 for walking and 2.15 for using an e-scooter (Wen et al., 2019). However, it is important to mention that e-scooter users tend to be more physically active as well (from other activities) compared to all non-regular users, even though this transport mode is less physically exhausting. However, a reversed causality is possible, meaning that the usage of an e-scooter doesn't necessarily lead to (a lot) more physical activity, but that more physically active people tend to use the e-scooter more often. It was in fact also this physical activity that had a positive effect on the hindering factor of physical capability, for which was shown that more physically active people didn't indicate as much that physical constraints were a mitigating factor in order not to use these transport modes.

Trip distances were also different between the transport modes. While cars are used through the whole spectrum of possible trip distances, their popularity is highest with longer trips, as for public transport. Bicycles are most popular up to distances of 2-5km, while for e-scooters distances of 5-10km are most popular, as also seen with e-bikes. This shows that conventional bicycles and e-scooters are not only seen as 'last-mile' options but as independent and fully fledged transport modes, which was also found by Degele et al. (2018), cited in (European Commission, 2021).

Surveys of e-scooter users and analysis of user data show that e-scooters are mainly used by young, employed men. There is also a significant proportion of users between 45 and 50 years old (European Commission, 2021; Vias institute, 2021). These findings could be confirmed in this research. While youngsters more and more find their way towards e-bikes (De Maeseneer, 2018; Federale Overheidsdienst Mobiliteit en Vervoer, 2022), it was found in this study that e-bike users tend be generally older, while conventional bicycle users show a more even spread. A share of 20.6% of e-bikes users younger than 36, found in this study, is in fact in line with other data recently gathered on cycling in Belgium (Federale Overheidsdienst Mobiliteit en Vervoer, 2022). Next, with regards to device choice, private e-scooters are popular for e-scooter users (Vias institute,

2021) and is confirmed in this research. However, shared use is also quite common. This differs for conventional bicycles and e-bikes that are more often privately-owned.

Lastly, it was found that e-scooters are quite popular among people with a physical disability. However, no insights could be given in the type of disability. Furthermore, it could be proven that they seem to have differing reasons for taking these transport modes, based on their needs, and have more problems in relation to the mitigating factors. Research on this topic is scarce (Dill & McNeil, 2020). Since interviews with providers showed that wheelchair users make use of shared e-scooters to propel their wheelchair for further distances, it is advised to perform additive research to better understand the possibilities of inclusion by means of this transport mode.

5.3 The environmental impact of e-scooters

Although e-scooters have no direct tailpipe emissions, concerns were raised due to the rumoured short lifetime and highly polluting battery production process. Life cycle assessments performed on the early generations of shared e-scooters found life cycle greenhouse gas (equivalent) emissions of 110-165 g CO_2 eq/vkm, on par with or just below a typical internal combustion engine car (Hollingsworth et al., 2019; Kazmaier et al., 2020; Moreau et al., 2020). These high emissions are primarily due to the presumed short lifetime of about 10 months or less and the use of polluting fossil fuel service vans used to transport and charge the e-scooters.

Of course, the largest portion of these emissions are caused by the vehicle production process, as well as operational services for the shared equivalents. A sensitivity analysis showed that the initial transport of the e-scooters (to Belgium) has a negligible contribution to the total life cycle emissions. Similarly, due to the very efficient drivetrain of the e-scooters, the GHG emissions associated to the production of the electricity required to charge the e-scooters only makes up about 2-5% of the total life cycle emissions.

In fact, the lifetime and lifetime mileage of the e-scooters have a large influence. An e-scooter that lasts longer and is used more often makes up for the relatively high manufacturing emissions, which is responsible for 50-80% of the total life cycle emissions. Therefore operators strive to keep their fleet of e-scooters operational for as long as possible by improving the design to be sturdier and by performing regularly scheduled maintenance.

Our result showed that the life cycle GHG emissions per vehicle-km are very sensitive to changes in the average daily distance travelled by e-scooters. This is because the vehicle and operational services components are much larger than the use component and thus vary greatly per vkm. In other words: the benefits of using the e-scooter more outweigh the direct impact from the higher energy use. Similarly, changes in the average lifetime of the e-scooter have significant impacts on the GHG emissions. A longer lifetime usually corresponds to a larger lifetime mileage and lower emissions per vkm. To add, lower servicing distances were also found to have an impact on GHG-emissions. The shift from free-floating devices to docking-station based supply, can help to reduce these servicing distances.

A questionnaire study performed in Brussels by Moreau et al. (2020) showed that car trips are frequently replaced by e-scooters. However, they also found that the e-scooter replaces public transport, bicycle, and walking trips. These findings seem to differ with the findings out of this questionnaire research, but can be explained by the way of investigating this modal shift. Moreau et al. (2020) asked the question: "Before the arrival of e-scooters, what mode of transportation would you have used for the same type of trips?" and thus focussed on one specific trip performed, while in this research usage was evaluated over a longer timespan (i.e. the share of transport mode use in general to perform trips). Determining modal shift solely based on a single trip doesn't give the full picture of trips made by a person (i.e. it does not have to mean that a person tends to replace public transport in general, when one single trip was made with an e-scooter instead of public transport). Also, Moreau et al. (2020) asked this question to everyone, even if they used the transport mode only once, while this questionnaire research focussed on more frequent users. Nevertheless, the possibility still arises that for some specific trips, a replacement is possible in terms of the transport mode chosen. However, this effect is estimated to be small if the use of transport modes in general is taken into consideration.

These findings in this research are in line in the context of international discussions coordinated by the International Transport Forum (OECD) on the environmental performance of the new mobility modes. Private bicycles, e-scooters, and mopeds are among the most efficient urban transport modes, performing a lot better than cars. Energy consumption and GHG emissions of shared micromobility (also including electric scooters, bicycles, electric bikes and mopeds) are to some extent even comparable to those of metro and buses (Delhaye & Vandael Schreurs, 2022).

While the lifetime of the e-scooters is a crucial parameter, estimating it is difficult since new models frequently pop up. The earliest generations had estimated lifetimes of 18 months or shorter, but some were still operational after 36 months. If operators are to be believed, the latest models may have lifetimes of up to 60 months. Assuming a conservative 36 months and daily mileage of 10 km yields life cycle GHG emissions of 49 g CO_2 eq/vkm, significantly less than the 84 g CO_2 eq/vkm estimate of the first generation. Under these circumstances, shared e-scooters perform slightly better than the average modal share in Brussels, which has life cycle GHG emissions of 60 g CO_2 eq/vkm, and can then be seen as a green mobility solution. We emphasize the importance of a high lifetime and daily mileage. An e-scooter that lasts only half as long and is ridden only half as much has life cycle GHG emissions almost four times as large and quickly becomes more polluting than fossil fuel cars.

This extreme sensitivity is one of the reasons this research tried to obtain accurate estimates of lifetimes and lifetime mileages from shared e-scooter providers. But despite best efforts, it was impossible to acquire this information. This form of secrecy surrounding the vehicles lifetime details indicates that their estimates should be taken with a grain of salt.

For private e-scooters the largest environmental benefits can still be booked in the vehicle production phase, since operational services are not relevant for these type of vehicles. Quickly summarised, two main options can be proposed: making the production process more environmental friendly, prolong the life of the devices by making them more robust and/or less technology dependent.

Note, that large quality differences can be present on the market between private e-scooters. Electric “toy like” kick scooters, with a cost of 100-200 euro, differ largely with 'street-worthy' vehicles with a cost usually above 500 euro. This difference can have a big impact on the vehicle’s life cycle and its life cycle emissions.

This analysis highlights the need for regulation and obligating transparent communication about the performance of micromobility devices in order to sustainably improve the impact on the environment. For this, a constructive solution has to be found without revealing business models of manufacturers and providers, which could possibly kill the potential of this transport mode.

Lastly, this environmental impact analysis largely focusses on GHG-emission in terms of CO_2. It is important to acknowledge that CO_2 emissions are only making up a part of the emissions factor and environmental impact (e.g. particulate matter from wearing of the tires/brakes, other green house gasses related to electricity production, other vehicle emissions from transport and operational services, environmental impact of mining the raw materials etc.). As such, this environmental impact analysis is a simplification of the total 'environmental impact' of e-scooters.

5.4 Behaviour

It was already stated in the introduction of this study that the riding behaviour of PMD (and especially e-scooter) users is crucial for road safety. (European Transport Safety Council, 2022). For that reason, a behavioural and conflict observation study was performed in pedestrian zones and shared spaces with a high share of pedestrians.

This research found that e-scooter riders had a higher risk on a conflict compared to bicycle users on a users level, but not on an interaction level. It was found, based on a manual selection of conflicts, that an important cause for these conflicts was speed: either speeding or speeds not adapted to the situation (both for bicycles and e-scooters). Based on aggregated conflict data, in 1 out of 4 conflicts the speed limit was not respected. Since e-scooter users sped more often compared to cyclists, a logical relation can be drawn between the higher speeds and higher risk on conflicts. However, at the time of a conflict, the compliance to the speed limit between e-scooter riders and cyclists did not differ. It was found that non-adapted speeds are also a main cause in crashes (European Transport Safety Council, 2022), proving the usefulness of surrogate safety measures in traffic safety research.

Che et al (2020), cited in (European Commission, 2021), found that pedestrians and cyclists feel safest when e-scooter users ride at a maximum speed of only 15 km/h. Che, Lum, & Wong (2020), cited in (European Commission, 2021) found that pedestrians feel safer when the e-scooter user overtakes at a maximum speed of 10 km/h. However, this was considered too slow by the participants driving an e-scooter and could also be observed, since e-scooter users in Austria travel at an average speed of 15.1 km/h (European Commission, 2021). These findings are confirmed in this research where it was found that 30% to 60% of the e-scooter users were speeding in pedestrian areas (walking pace speed limit). However, due to the geofencing possibilities of shared providers, together with the adapted legislation on July 1st 2022, it is possible that speeds can be limited on shared e-scooters in these shared spaces by the providers themselves. However, an evaluation study would be required to effectively confirm if this geofencing is done by shared providers..

Based on the manual selection of conflicts, risky behaviour were found to be more often performed by male users. This translates in a higher share of male riders being injured (Vias institute, 2021). However, a fully conclusive statement cannot be made, since it is possible that the higher exposure of male users plays a role, as well as their suspected more risky behaviour, which could not be controlled for in this study.

For this conflict observation study, it has to be mentioned that possible conflicts could be missed via the automated software. However, if manual coding had to be performed, a limited number of hours would have to be selected, also potentially leading to a miss of conflicts.

To cope with the rising attention for e-scooters and concerns about how this new transport mode is being used, a new legislation on micromobility devices was set in place in Belgium on the 1st of July 2022, partly equating e-scooter users with cyclists. For e-scooters, this legislation is only applicable for approved versions, with a maximum speed of 25km/h, and without a seat, since other models are prohibited or falling under the specific moped legislation with driving license AM. This adaptation was made in order to tackle some issues around e-scooters, as well as other personal light electric vehicles (e.g. monowheel, hoverboards, Segway, etc.), and focussed on the following aspects:

- A prohibition of using an e-scooter under the age of 16 (except for dedicated zones)
- A prohibition of the use of an e-scooter on sidewalks
- A prohibition of riding with a passenger
- An obligation to use dedicated parking spots for shared providers
- An obligation to ride at walking pace in pedestrian areas where an e-scooter is allowed

However, the effects of this legislative change have to be researched, to determine whether or not these restrictions are complied with.

To add, a universal sound for e-scooters is thought to improve road safety (TIER, n.d.). However, given the results from the conflict observation, it can be concluded that the sound of an e-scooter may not necessarily be a solution, since speeding has a large cause in conflicts, and not necessarily the unknown presence of an e-scooter. The behaviour of the user has to play a large role in mitigating negative safety impacts. In fact, this would also require more alertness from pedestrians, while one could question if pedestrians should be constantly alert in pedestrian areas.

While the behavioural and conflict observation section of this study took quite some e-scooter and bicycle users into account, some possible behaviours were not investigated. The positioning of riders on their e-scooter was for example not researched (e.g. whether or not riders stand with their feet next to each other or stable in front of each other). Also, were conflicts between pedestrians and parked or tipped over e-scooters not tackled. In fact, these conflicts are not able to be researched by the classical conflict observation techniques and would require, together with the positioning on the e-scooter, a dedicated behavioural observation.

Lastly, caution is also needed in the interpretation of conflict risk. This study only took shared spaces into account with a focus on vulnerable road users. Interactions with motorised traffic were merely taken into account (only at the Elsensesteenweg). Subsequent studies, focussing on interactions with PMDs and motorised traffic are advised in order to gain more insights in these potential unsafe situations. In fact, as (De Vos & Slootmans, 2023; Shah et al., 2021) show, quite some crashes occur with turning motorised vehicles.

5.5 Crashes

The self-reported crashes collected for this research, showed that conventional bicycles had the highest crash involvement, after which e-scooters follow, and lastly e-bikes. For near-crashes, this was roughly equal. At first glance, one could conclude that e-scooters are safer compared to bicycles, but this conclusion cannot be drawn. Since exposure wasn't collected in this questionnaire, no statements can be made about crash risk. In fact, in the literature it is even stated, based on very limited crash statistics, that e-scooters have a crash risk that is 4-10 times higher compared to conventional bicycles (European Transport Safety Council, 2022; SWOV, 2021).

It is suspected that only a fraction of the crashes is registered by the police, since it was found that only 10% of the crashes resulted in a more severe injury for which a doctor visit was needed. This can be endorsed by the recent focus on hospital data for e-scooter crashes and lower support for PV-analyses due to underreporting (Bjørnskau, 2022; European Transport Safety Council, 2022). Furthermore, it was found that there is no difference in the risk of rider fatality per trip between e-scooters and bicycles, but that the risk for hospitalisation appears significantly higher with e-scooter riders compared to cyclists (European Commission, 2021). While the crash severity does not immediately seem very serious, it has to be kept in mind that e-scooters are mainly used by younger people, that are less vulnerable compared to older users of other transport modes.

Self-reported data showed that PMD crashes are largely unilateral (i.e. 4 crashes out of 5), which is the opposite of PV analyses (De Vos & Slootmans, 2023), but conform (European Commission, 2021; Vias institute, 2021). Causation for these unilateral crashes are often related to technical problems, own behaviour, and weather conditions for e-scooters, while cyclists mainly report road infrastructural problems and their own behaviour as crash causations. In multilateral crashes the behaviour of the other road users is often indicated as a crash causer, but own behaviour is also mentioned by e-scooter users. These findings seems to be somewhat in line with PV information (De Vos & Slootmans, 2023), except for unilateral crashes, for which a high likelihood of underreporting is present, since most of these crashes were found to have little to no physical consequences. The injury severity increases when another road user is present in the crash. The high share of technical issues, as a crash causation for e-scooters, can not be explained. Further research on this aspect is advised.

Specific injuries were not included in the questionnaire, but literature highlights the high presence of head injuries in e-scooter crashes (Bjørnskau, 2022; European Transport Safety Council, 2022). Nevertheless, a helmet obligation has not been introduced due to the fear of impacting the attractiveness of the transport mode, which led to critique on legislators (Vias institute, 2021).

Lastly, it was already found in the mobility section that e-scooter users possess less frequently any kind of driving license compared to regular users and non-regular users of the other transport modes. Because of this, it is plausible that a lack of adequate knowledge is present (i.e. knowledge that is often obtained for a theoretical exam to achieve a driving license), which could be an explanation for the higher ratio of crashes per vehicle kilometer travelled (also found in (Vias institute, 2021)).

6 Recommendations

In order to better counter the possible negative effects, but also to promote correct use and capitalise on possible opportunities, the following recommendations can be proposed.

Framework

- More clearly defined categorisations in the field of PMDs with common definitions are required nationally and internationally. Ideally cohesion should be present on a European level.
- Type approval on European level to make sure that legal and illegal PMDs can be much easier distinguished. Furthermore, this can clarify the grey zone of e-scooters equipped with a saddle and "fast" e-scooters (i.e. speed higher than 25km/h.
- Increased harmonisation of legislation/rules between different member states, ensuring they are well communicated and enforced.
- Clearer goals for PMD use on a policy level that is believed to be an opportunity on mobility level.

Mobility

- Stimulate PMD use based on the ERG-theory and fulfilment of needs
    - Communicate about the higher order motivators and the role PMDs have to fulfil these needs
    - Show the practicality of PMDs in everyday settings
- Reduction of barriers to PMD use where sustainable mode shift can be achieved based on the behaviour change wheel and its interventions and policies
- Promote further research on PMDs, and especially their role for physically challenged road users
- Treat e-scooters as a fully-fledged distinct transport mode and not a toy
- Consider and promote PMDs as a substitute for car trips

Environmental impact

- Create transparency in the field of PMDs, by setting up a regulatory framework concerning the life cycle of e-scooters and their impact on the environment (obligatory for shared providers)
- Move the production or large scale assembly of PMDs to Europe where stricter emission rules apply
- Consider labelling of PMD depending on their environmental impact score in the production phase
- Impose actions to reduce the impacts relating to manufacturing PMDs, including material use
- Promote and/or subsidise maintenance and repair of PMDs to expand their lifespan
- Promote and/or subsidies more environmentally friendly produced PMDs and demote PMDs of poor quality built with environmentally unfriendly materials
- Reward shared scheme operators for sustainable actions in the field of servicing, redistribution and environmental friendly devices, instead of only fining unwanted behaviours
- Place a fixed cap/goal on the lifetime of e-scooters that has to be achieved (e.g. require a guaranteed 36 month lifetime) by operators in the field, and impose sanctions if this is not reached.

Safety

- Continue collection of crash information of PMDs and improve registration (distinguish between types of e-scooters)
- Enforcement of inappropriate speed and alcohol use with e-scooter users, and of the new legislation in force since July 2022. Stricter enforcement is especially warranted in crash-sensitive areas such as zones with many cyclists and pedestrians.
- Increase helmet use through campaigns
- Consider safer vehicle design standards and regulations
- Improve infrastructure for PMDs (traffic engineering interventions, e.g. improvement of surface conditions, separate space for e-scooters to mitigate conflicts with pedestrians)
- Create alternatives to fines to aim for behavioural change (e.g. training)
- Create a self-training course via a smartphone to increase the likelihood of following a basic vehicle control training, to avoid professional training courses which will almost never be voluntarily followed. Training programs could also increase knowledge about the legislation and reduce risky behaviours.
- Further research is necessary to better understand how e-scooter users interact with people walking, cycling, and driving to prevent crashes from happening.
- Further research is advised to investigate the high share of technical issues resulting in crashes with e-scooters.

The use of direction indicators, a sound signal, rear-view mirrors and reflective materials are not recommended since they were not believed to be a main cause of crashes or conflicts. In fact, these additions to the vehicle will impose an extra cost to the user, impossibility for shared providers to keep their scooters legally compliant (e.g. due to vandalism, drops, etc.), and can have an impact on their portability which is a key factor for multimodality.

References

ACEM. (2021). *Micromobility: The case of the Personal Light Electric Vehicle*. https://acem.eu/policy-areas/mobility/acem-position-paper-micromobility-the-case-of-the-personal-light-electric-vehicle

Battery Solutions. (2022). *The Unwritten risks of E-mobility batteries | Battery Solutions*. https://batterysolutions.com/news/the-unwritten-risks-of-e-mobility-batteries/

Bird Cities Blog. (2022). *Bird BMS: The Secret to Safe, Sustainable Scooter Batteries*. https://www.bird.co/blog/bird-bms-safe-sustainable-scooter-batteries/

Bjørnskau, T. (2022). *E-scooter accidents and risks - comparing data from Norway (Oslo) with other countries*.

Bláfoss Ingvardson, J., Thorhauge, M., Kaplan, S., Nielsen, O. A., & Raveau, S. (2019). *Incorporating Existence, Relatedness & Growth needs in transport mode choice: A hybrid choice framework*. https://transp-or.epfl.ch/heart/2019/abstracts/hEART_2019_paper_162.pdf

Bolt Blog. (2020). *Bolt launches new, fourth-generation scooter model | Bolt Blog*. https://blog.bolt.eu/en/bolt-launches-new-fourth-generation-scooter-model/

Brannigan, C., Waymel, L., Giff, H., & Kilsten, A. (2022). *Expert study: 'Safety and environmental aspects of the use of Personal Mobility Devices*. https://www.fiaregion1.com/expert-study-on-safety-and-environmental-aspects-of-the-use-of-personal-mobility-devices/

Brown, G. R. (1994). Traffic conflicts for road user safety studies. *Canadian Journal of Civil Engineering*, *21(1)*, 1–15. https://doi.org/https://doi.org/10.1139/l94-001

Carpenter, S. (2019, October 25). In the Van With the 'Juicers' Who Round Up and Recharge Lime Scooters. *The New York Times*. https://www.nytimes.com/2019/10/25/business/lime-bird-scooters-rechargers.html

Castro, A., Gaupp-Berghausen, M., Dons, E., Standaert, A., Laeremans, M., Clark, A., Anaya-Boig, E., Cole-Hunter, T., Avila-Palencia, I., Rojas-Rueda, D., Nieuwenhuijsen, M., Gerike, R., Panis, L. I., de Nazelle, A., Brand, C., Raser, E., Kahlmeier, S., & Götschi, T. (2019). Physical activity of electric bicycle users compared to conventional bicycle users and non-cyclists: Insights based on health and transport data from an online survey in seven European cities. *Transportation Research Interdisciplinary Perspectives*, *1*, 100017. https://doi.org/10.1016/J.TRIP.2019.100017

Cazzola, P., & Crist, P. (2020). *Good to Go? Assessing the Environmental Performance of New Mobility*. https://www.itf-oecd.org/sites/default/files/docs/environmental-performance-new-mobility.pdf

Clean Energy Institute. (2020). *Lithium-Ion Battery - Clean Energy Institute*. https://www.cei.washington.edu/education/science-of-solar/battery-technology/

Conti, A. (2019). *Someone's Going to Get Killed Charging Those E-Scooters*. Vice. https://www.vice.com/en/article/wjmx8y/someones-going-to-get-killed-charging-those-e-scooters-juicing-limes

Dardenne, L. (2022, April 28). La trottinette électrique n'est pas un jeu, un accident peut laisser des séquelles physiques, fonctionnelles, esthétiques et psychiques. *La Libre Belgique*. https://www.lalibre.be/planete/sante/2022/04/28/la-trottinette-electrique-nest-pas-un-jeu-elle-peut-laisser-des-sequelles-physiques-fonctionnelles-esthetiques-et-psychiques-2LM2NGKNDZGXTISO7CGSEOVPO4/

de Bortoli, A. (2021). Environmental performance of shared micromobility and personal alternatives using integrated modal LCA. *Transportation Research Part D: Transport and Environment*, *93*. https://doi.org/10.1016/j.trd.2021.102743

De Ceunynck, T. (2017). *Defining and applying surrogate safety measures and behavioural indicators through site-based observations* [Lund University]. https://documentserver.uhasselt.be/handle/1942/24288

De Ceunynck, T., Wijlhuizen, G. J., Fyhri, A., Gerike, R., Köhler, D., Ciccone, A., Dijkstra, A., Dupont, E., & Cools, M. (2021). Assessing the Willingness to Use Personal e-Transporters (PeTs): Results from a Cross-National Survey in Nine European Cities. *Sustainability 2021, Vol. 13, Page 3844*, *13*(7), 3844.

https://doi.org/10.3390/SU13073844

De Maeseneer, W. (2018). *Elektrische fiets steeds populairder, ook bij jongeren*. VRT Nieuws. https://www.vrt.be/vrtnws/nl/2018/03/29/elektrische-fiets-steeds-populairder--ook-bij-jongeren/

De Vos, N., & Slootmans, F. (2023). *Analyse approfondie des caractéristiques et profils d'accidents impliquant une trottinette électrique*.

Delhaye, A., & Vandael Schreurs, K. (2022). *Duurzame integratie van gemotoriseerde tweewielers (G2Ws) in het mobiliteitsbeleid - Een stand van zaken en prognoses*. https://www.vias.be/nl/onderzoek/onze-publicaties/duurzame-integratie-van-gemotoriseered-tweewielers/

Dill, J., & McNeil, N. (2020). Are Shared Vehicles Shared by All? A review of Equity and Vehicle Sharing. *Journal of Planning Literature*. https://doi.org/10.1177/0885412220966732

Dott. (2022). *Sustainability GRI Report*.

Dott Blog. (2021). *Why swappable batteries are the way to go | Dott blog*. https://ridedott.com/blog/global/why-swappable-batteries-are-the-way-to-go

Electric Scooter Guide. (2022a). *Electric Scooter Regenerative Brakes » Electric Scooter Guide*. https://electric-scooter.guide/guides/electric-scooter-regenerative-brakes/

Electric Scooter Guide. (2022b). *Technical Guide: Electric Scooter Brakes » Electric Scooter Guide*. https://electric-scooter.guide/guides/electric-scooter-brakes/

Ericsson. (2021). *Connected Micromobility*. https://www.ericsson.com/4aadf6/assets/local/internet-of-things/docs/10272021-ericsson-connected-micromobility.pdf

European Commission. (2021). *Road safety thematic reports - Personal Mobility Devices*. https://road-safety.transport.ec.europa.eu/system/files/2021-07/road_safety_thematic_report_personal_mobility_devices_tc_final.pdf

European Transport Safety Council. (2022). *e-Scooter Safety: From research to action*. https://etsc.eu/etsc-online-event-e-scooter-safety/

EY. (2020). *Micromobility: Moving cities into a sustainable future*.

Federale Overheidsdienst Mobiliteit en Vervoer. (2022). *Enquête BEMOB: Fietsgebruik in België*. https://mobilit.belgium.be/nl/duurzame-mobiliteit/fietsen/elektrische-fietsen

Fluctuo. (2022). *European Shared Mobility Index - Annual Review 2021*.

FOD Mobiliteit en Vervoer. (2022). *Enquête monitor over de mobiliteit van de Belgen*. https://mobilit.belgium.be/nl/publications/enquete-monitor-over-de-mobiliteit-van-de-belgen

Gauquelin, A. (2020). *Jump: the next battery-swap technology?* Shared-Micromobility. https://shared-micromobility.com/jump-the-next-battery-swap-technology/

Hayward, J. C. (1972). Near-miss determination through use of a scale of danger. *Highway Research Record*, *384*, 24–34.

Hendrickx, K. (2019, January 23). Op nachtelijke stepjacht: veel stress, weinig euro's. *Bruzz*. https://www.bruzz.be/economie/op-nachtelijke-stepjacht-veel-stress-weinig-euros-2019-01-23

Hollingsworth, J., Copeland, B., & Johnson, J. X. (2019). Are e-scooters polluters? the environmental impacts of shared dockless electric scooters. *Environmental Research Letters*, *14*(8). https://doi.org/10.1088/1748-9326/ab2da8

Horizon Micromobility. (2022). *Electric Scooter Motor Guide - information on e-scooter motors – Horizon Micromobility*. https://horizonmicromobility.com/pages/scooter-motors

IEA. (2022). *Belgium - Countries & Regions - IEA*. https://www.iea.org/countries/belgium

Intelligent Transport. (2022). *TIER Mobility arrives in Belgium with e-scooter launch in Brussels*. https://www.intelligenttransport.com/transport-news/133134/tier-mobility-e-scooters-brussels/

ITF assessment tool. (2020). *life-cycle-assessment-calculations-2020*.

Johnsson, C., Laureshyn, A., & De Ceunynck, T. (2018). In search of surrogate safety indicators for vulnerable road users: a review of surrogate safety indicators. *Transport Reviews*. https://doi.org/https://doi.org/10.1080/01441647.2018.1442888

Jossen, A., Späth, V., Döring, H., & Garche, J. (1999). Reliable battery operation — a challenge for the battery management system. *Journal of Power Sources*, *84*(2), 283–286. https://doi.org/10.1016/S0378-7753(99)00329-8

Kamaluddin, N. A., Andersen, C. S., Larsen, M. K., Meltofte, K. R., & Várhelyi, A. (2018). Self-reporting traffic crashes – a systematic literature review. *European Transport Research Review 2018 10:2*, *10*(2), 1–18. https://doi.org/10.1186/S12544-018-0301-0

Kazmaier, M., Taefi, T., & Hettesheimer, T. (2020). Techno-Economical and Ecological Potential of Electric Scooters: A Life Cycle Analysis. *European Journal of Transport and Infrastructure Research*, *20*(4), 233–251. https://doi.org/10.18757/EJTIR.2020.20.4.4912

Klimt, A. (2022). *Alex Klimt on LinkedIn: #powerbanks #Ukraine #RideTogether*. https://www.linkedin.com/posts/alexklimt_powerbanks-ukraine-ridetogether-activity-6942447992385802240-GMs5?utm_source=linkedin_share&utm_medium=member_desktop_web

Lawrence, C. (2021). *Fixed vs. detachable ebike batteries: Which one is right for you?* The Next Web. https://thenextweb.com/news/what-kind-of-ebike-battery-is-best-for-you

Licata, V. (2021). *Mobilité électrique et partagée : une solution durable ? Analyse du cycle de vie des scooters électriques en libre-partage à Bruxelles*. Université Libre de Bruxelles.

Lime. (2019). *A study on Lime's environmental impact in Paris*.

Martensen, H., Temmerman, P., & Pelssers, B. (2021). *Interacties in voetgangersgebieden - Onderzoek naar de interacties tussen bestuurders en voetgangers in voetgangersgebieden*. https://www.vias.be/nl/onderzoek/onze-publicaties/interacties-in-voetgangersgebieden/

Michie, S., van Stralen, M. M., & West, R. (2011). The behaviour change wheel: A new method for characterising and designing behaviour change interventions. *Implementation Science*, *6*(1). https://doi.org/10.1186/1748-5908-6-42

Moreau, H., de Jamblinne de Meux, L., Zeller, V., D'Ans, P., Ruwet, C., & Achten, W. M. J. (2020). Dockless E-Scooter: A Green Solution for Mobility? Comparative Case Study between Dockless E-Scooters, Displaced Transport, and Personal E-Scooters. *Sustainability*, *12*(5). https://doi.org/10.3390/su12051803

Polis. (2022). *Latest European Shared Mobility Index published*. https://www.polisnetwork.eu/news/latest-european-shared-mobility-index-published/#:~:text=The European Shared Mobility Index provides a quarterly snapshot of,%2C scooters%2C mopeds and cars.

POLIS Network. (2022). *A look at the European Shared Mobility Industry: Fluctuo's latest Index - POLIS Network*. https://www.polisnetwork.eu/news/a-look-at-the-european-shared-mobility-industry-fluctuos-latest-index/

Pulvirenti, G., De Ceunynck, T., Daniels, S., Distefano, N., & Leonardi, S. (2021). Safety of bicyclists in roundabouts with mixed traffic: Video analyses of behavioural and surrogate safety indicators. *Transportation Research Part F*, *76*, 72–91. https://doi.org/10.1016/j.trf.2020.11.006

Romain, M. (2022). *"The oldest shared escooter in operations". 3.5 years later, our Generation - Maxim Romain on LinkedIn | 20 comments*. https://www.linkedin.com/feed/update/urn:li:activity:6940607194199437312/

Schuller, A., & Aboukrat, M. (2019). *White paper: The Role of e-scooters and Light Electric Vehicles in Decarbonizing Cities*.

Severengiz, S., Finke, S., Schelte, N., & Wendt, N. (2020, March 1). Life Cycle Assessment on the Mobility Service E-Scooter Sharing. *2020 IEEE European Technology and Engineering Management Summit, E-TEMS 2020*. https://doi.org/10.1109/E-TEMS46250.2020.9111817

Shah, N. R., Aryal, S., Wen, Y., & Cherry, C. R. (2021). Comparison of motor vehicle-involved e-scooter and bicycle crashes using standardized crash typology. *Journal of Safety Research*, *77*, 217–228. https://doi.org/10.1016/J.JSR.2021.03.005

Strobel, P. (2021). *Electric Scooter Tires: A Technical Guide for Beginners*. https://eridehero.com/electric-scooter-tires/

SWOV. (2021). *Light electric vehicles (LEVs)*. https://swov.nl/sites/default/files/bestanden/downloads/FS LEVs UK.pdf

The Brussels Times. (2020). *E-scooter popularity will boom in Brussels after lockdown*. https://www.brusselstimes.com/109131/e-scooter-popularity-will-boom-in-brussels-after-lockdown

The Next Web. (2022). *Micromobility startups struggle to profit despite heavy funding -- here's why*. https://thenextweb.com/news/micromobility-expansion-is-in-order-now-time-for-profits

The Verge. (2019). *Bird has a new electric scooter: it's durable, comes in three different colors, and you can buy it - The Verge*. https://www.theverge.com/2019/5/8/18535698/bird-one-electric-scooter-ride-share-own-price

TIBCO. (n.d.). *What is Factor Analysis?* https://www.tibco.com/reference-center/what-is-factor-analysis

TIER. (n.d.). *UCL and London e-scooter operators team up to research 'universal sound' for e-scooters in the capital*. https://about.tier.app/ucl-and-london-e-scooter-operators-team-up-to-research-universal-sound-for-e-scooters-in-the-capital/

Tire meets road. (2018). *The insane way some electric scooters are being charged, gas generators on a truck - Alt Car news*. https://tiremeetsroad.com/2018/10/07/the-insane-way-some-electric-scooters-are-being-charged-gas-generators-on-a-truck/

Van der Horst, H. (1990). *A time-based Analysis of road-User Behaviour at Intersections*. 91–107.

Vezzini, A. (2014). Lithium-Ion Battery Management. *Lithium-Ion Batteries: Advances and Applications*, 345–360. https://doi.org/10.1016/B978-0-444-59513-3.00015-7

Vias institute. (2021). *Briefing 'Elektrische steps en verkeersveiligheid'*. https://www.vias.be/nl/onderzoek/onze-publicaties/briefing-elektrische-steps-verkeersveiligheid-2021/

Voi Blog. (2021). *Voi unveils the Voiager 4, an e-scooter truly built for cities for living, featuring noise and optional air-quality sensors -*. https://www.voiscooters.com/blog/voi-unveils-the-voiager-4/

Wen, Y., Bassett Jr, D. R., Zhang, S., Brakewood, C., Cherry, C. R., Thorsen, T., Weinhandl, J. T., & Morse, J. (2019). *Evaluating the Physical Activity Impacts of Riding Electric Kick Scooters*. https://trb.secure-platform.com/a/solicitations/18/sessiongallery/325/application/1436

World Energy Data. (2022). *World Electricity Generation - World Energy Data*. https://www.worldenergydata.org/world-electricity-generation/

Attachments

Factor analyse ERG theorie (Engelstalig)

A factor analysis was performed on all 33-items in order to subtract the different ERG-level needs. In order to determine the number of factors, an eigenvalue of >1 was used. Plotting the eigenvalues off all the factors on a screen plot showed that 3 factors could be derived, on which 31 items gave a high factor loading. For the individual factor loadings per item, a cut-off value larger than 0.3 was used. A variance of 53.72% was explained by the 3 factors. The table below gives an overview of the factor loadings, mean factor scores, standard deviation, and reliability scores. The following factor naming could be determined: 'Utilitarian mobility' (consisting of mostly existence-level needs), 'Subjective norm' (consisting of mostly relatedness-level needs), and 'Attitudes as secondary motivators' (consisting mostly of growth-level needs).

	Items	Factors		
		Attit.	Utili.	Subj.
1.	I believe it is good for the environment	**0.821**	0.137	0.059
2.	I believe is better for my health to use this rather than other transport modes	**0.789**	0.208	0.121
3.	I believe it is good for my health	**0.788**	0.213	0.102
4.	I believe it helps to improve the situation in cities (congestion, pollution, noise etc.)	**0.782**	0.22	0.056
5.	I think it is well perceived by the society to use it	**0.71**	0.264	0.112
6.	I believe it allows to contribute to a better society	**0.709**	0.234	0.292
7.	I find it gives a good feeling to use it (adrenaline, freedom etc.),	**0.67**	*<u>0.342</u>*	0.212
8.	I believe it is cheaper than other transport modes	**0.645**	0.125	0.109
9.	Using it to clear my head and stimulate productivity	**0.622**	*<u>0.416</u>*	0.066
10.	I believe is easier to park / does not require parking	**0.615**	0.206	0.045
11.	I believe it offers more flexibility than other transport modes	**0.583**	0.289	0.233
12.	I believe my family/friends would think it is nice that I use it	*<u>0.523</u>*	0.284	**0.44**
13.	I think it becomes trendy to use it	*<u>0.411</u>*	0.152	**0.361**
14.	Going to a museum / art exhibition	0.17	**0.748**	0.171
15.	Attending after-hours activities (e.g., a language course, music class etc.)	*<u>0.355</u>*	**0.725**	-0.035
16.	Meeting your friends during a day	*<u>0.415</u>*	**0.712**	-0.021
17.	Going for a professional meeting	0.111	**0.711**	0.293
18.	Going out in the evening (e.g. going to dinner, go party, go to the bar, etc.)	0.119	**0.679**	0.233
19.	Going for a trip /excursion	0.187	**0.655**	0.215
20.	Going to work/school	*<u>0.378</u>*	**0.644**	0.044
21.	Running daily errands (e.g., going to the doctor, going to the hairdresser, going to the pharmacy)	*<u>0.375</u>*	**0.643**	-0.024
22.	Picking up take-away food	0.199	**0.638**	0.185
23.	Meeting new people	0.245	**0.624**	0.289
24.	Spending some quality time with your family	*<u>0.455</u>*	**0.538**	0.118
25.	Making a multimodal journey (combining different transport modes, e.g., taking a bike on the train)	0.145	**0.529**	0.123
26.	Doing local groceries (e.g., in the street market, local supermarket)	*<u>0.382</u>*	**0.519**	0.067
27.	I believe it allows to impress friends, co-workers, family	0.062	0.124	**0.768**
28.	I believe it gives a kind of social prestige/benefit to use it	0.264	0.217	**0.694**
29.	I believe it allows to demonstrate your opinion/beliefs	*<u>0.342</u>*	0.224	**0.635**
30.	I believe it is safer than other transport modes	0.272	*<u>0.318</u>*	*<u>0.572</u>*
31.	I believe that people who use it belong to a certain (social) group/movement	-0.041	-0.133	**0.544**
32.	Going to a bigger store (e.g., hypermarket, Ikea etc.)	-0.126	**0.434**	*<u>0.525</u>*
33.	I believe it is quicker than other transport modes	0.279	0.298	*<u>0.429</u>*
	Mean	3.485	2.975	2.879
	Standard Deviation	0.821	0.832	0.711
	Chronbach's Alpha	0.927	0.917	0.768

Items in italic and underlined loaded onto the factor but were left out due to a lower alpha value or cross loading that couldn't be explained on a factor. Bold items are part of the factor and were taken to calculate a mean score for the factor.

Some cross-loadings could be observed, possibly due to a an item that can be seen under multiple factors. However, an appropriate match with the factor was determined based on the cohesion with other items in a respective factor, and the reliability analysis.

COM-B theory factor analysis

A factor analysis was performed on all 31-items that were constructed in terms of the COM-B framework. An eigenvalue of >1 was used in order to determine the number of factors. Plotting the eigenvalues of all the factors on a screen plot showed that 5 factors could be derived. However, after cross checking the items with the 5-factor structure, it was noticed that all items loaded on the first factor, with some cross loadings on the other factors. Because of this, a fixed 3-factor structure was proposed based on the 3 main factors of the COM-B model. For the individual factor loadings per item, a cut-off value larger than 0.3 was used. A variance of 54.86% was explained by the 3 factors. The table below gives an overview of the factor loadings, mean factor scores, standard deviation, and reliability scores. The following factor naming could be determined based on the loadings of the items: 'Capability', 'Opportunity', and 'Motivation'.

	Items	Factors		
		Motiv.	Oppor.	Capab.
1.	[…] would need to get fun out of using this mode (e.g. feel happy that I don't take the polluting car or get relaxed from the morning air)	**0.739**	0.117	0.231
2.	[…] would need to have suitable road infrastructure available to use it safely (e.g. not too many pedestrians, the road should be even, wider bicycle lanes)	**0.727**	-0.008	0.133
3.	[…] would need to be able to store my transport mode to make sure I can leave it safely behind (e.g. have a dedicated storage room or bicycle storage)	**0.712**	0.100	0.074
4.	[…] would need to feel that it is safe to use (e.g. having read somewhere that it is a safe transport mode)	**0.691**	0.208	0.217
5.	[…] would automatically need to feel that I want to use this mode (e.g. automatically think of using this mode since I like physical activity or like the fresh morning air, etc.))	**0.673**	0.233	0.253
6.	[…] would have to develop a habit of using the transport mode (e.g. would need to make a habit of going with this mode to the station)	**0.655**	*0.315*	0.218
7.	[…] would need to make a plan to use the transport mode (e.g. think about the alternative routes I can take, plan my trip better in advance)	**0.608**	*0.332*	*0.305*
8.	[…] would need to have suitable additive user equipment (e.g. would need to have all-weather gear to be able to use it even when it rains, a reflective jacket or light helmet)	**0.600**	0.269	0.244
9.	[…] would have to have some facilities at my main activity that make it able for me to use it (e.g. ability to shower, ability to charge it, etc.)	*0.564*	**0.367**	0.121
10.	[…] would need to feel that it is natural for me to use it (i.e. I feel bad if I am using a different transport mode, while knowing the e-scooter would have been better).	**0.559**	*0.364*	0.198
11.	[…] would have to belief that I contribute to environmental sustainability (e.g. I would need to be convinced that using this transport mode is good for the environment)	**0.487**	*0.452*	0.181
12.	[…] would need to overcome negative feelings that automatically seep in (e.g. overcome the automatic thought that it is unsafe to use this transport mode, because I saw someone having an accident or falling).	**0.444**	*0.361*	*0.442*
13.	[…] would need to live less remotely that makes it possible to use the transport mode (e.g. I would need to live somewhere, where the distance to an activity isn't that big)	*0.378*	0.249	0.262
14.	[…] would have to have more support from others to use the transport mode (e.g. have friends that support me and don't laugh with me for using it)	0.162	**0.761**	0.265
15.	[…] would need to feel that I'm part of a community (e.g. live in a city where most people use it as a transport mode as part of their life)	0.101	**0.743**	0.250
16.	[…] would need to have more people in my close environment around me that use the transport mode (e.g. colleagues that use the transport mode, my family, my friends)	0.196	**0.723**	0.260
17.	[…] would need to have more triggers to be prompted to use the transport mode (e.g. someone that passes me every morning and is faster at work than me, other people that use it look more healthy, etc.)	0.286	**0.632**	0.230
18.	[…] would need to know more about the benefits of this transport mode (e.g. know how it contributes to greener mobility or improved living quality, or knowing how much time it would save me if I used it, etc.)	0.174	*0.583*	**0.401**
19.	[…] would have to have better maintained shared devices so that I would want to use it more (e.g. replace damaged scooters, better cleaned, etc.)	*0.454*	**0.557**	0.104
20.	[…] would need to have the transport mode more accessible/available (e.g. need to have a personal device or should be able to make use of a shared device)	*0.449*	**0.524**	0.210
21.	[…] would need to have more money to use this transport mode	*0.314*	**0.522**	0.118

22.	[…] would need to have an adapted device in order for me to be able to use it (e.g. a different seat mounted, etc.)	*0.330*	**0.521**	*0.372*
23.	[…] would need to know more background info about how the device works. (e.g. how to charge it, how fast it goes, etc.)	0.135	*0.508*	**0.476**
24.	[…] would need to have more time to use this transport mode.	*0.407*	**0.413**	0.163
25.	[…] would need to have more physical endurance to not be fatigued immediately. (e.g. develop greater stamina to not be exhausted after a ride)	0.237	0.112	**0.813**
26.	[…] would need to be physically stronger (e.g. build up stronger legs to be able to conquer a steep hill, or be stronger to carry it in the train)	0.230	0.148	**0.793**
27.	[…] would need to find a solution to overcome physical limitations (e.g. get around problems about seating or standing position on the transport mode)	0.201	*0.308*	**0.729**
28.	[…] would have to have more mental endurance to make sure that I keep focussed while using this transport mode. (e.g. stay focussed in a city centre with dense traffic after a 20min ride)	0.174	0.295	**0.729**
29.	[…] would have to have more mental strength to not easily give up or pick another transport mode. (e.g. take the car because there is a strong wind outside or because it is raining)	*0.320*	0.186	**0.663**
30.	[…] would need to develop more confidence in using the device (e.g. be convinced that I can easily reach my destination)	0.270	*0.326*	**0.629**
31.	[…] would have to have better skills to operate the device (e.g. follow a practical training to safely use the device)	0.107	*0.464*	**0.620**
	Mean	3.278	2.871	2.866
	Standard Deviation	0.800	0.806	0.895
	Chronbach's Alpha	0.904	0.892	0.911

Items in italic and underlined loaded onto the factor but were left out due to a lower alpha value or cross loading that couldn't be explained on a factor. Bold items are part of the factor and were taken to calculate a mean score for the factor.

This 3 factor-structure was highly consistent with the COM-B model framework, with appropriate item loadings on the respective factors. Cross-loadings could be observed, possibly due to a an item that can be seen under multiple factors or the lower cut-off value of 0.3. However, an appropriate match with the factor was determined based on the cohesion with other items in a respective factor, and the reliability analysis. In order to investigate the 6-factor structure from the COM-B model (i.e. main 3 factor structure, with each factor having 2 sublevels) a factor analysis was ran on each individual factor. For the Opportunity and Motivation factors a 2-factor solution was found, when the number of factors were determined based on an eigenvalue >1. For the factor capability, a fixed 2-factor structure had to be proposed since the factor analyses based on an eigenvalue of >1 only showed a 1-factor solution. In this case, each COM-B factor had a 2-factor structure showing the different COM-B sub-items. A cut-off value of 0.3 was used. It was not possible to preserve all items in this 6-factor structure. 25 items out of a total of 31 items were kept. Further, were some cross loadings found. The outcome can be found in the table below.

Capability		
	Physical	Psychological
[…] would need to have more physical endurance to not be fatigued immediately. (e.g. develop greater stamina to not be exhausted after a ride)	**0.878**	0.191
[…] would need to be physically stronger (e.g. build up stronger legs to be able to conquer a steep hill, or be stronger to carry it in the train)	**0.849**	0.221
[…] would need to find a solution to overcome physical limitations (e.g. get around problems about seating or standing position on the transport mode)	**0.691**	*0.438*
[…] would have to have better skills to operate the device (e.g. follow a practical training to safely use the device)	**0.422**	*0.702*
[…] would have to have more mental endurance to make sure that I keep focussed while using this transport mode. (e.g. stay focussed in a city centre with dense traffic after a 20min ride)	*0.662*	**0.461**
[…] would have to have more mental strength to not easily give up or pick another transport mode. (e.g. take the car because there is a strong wind outside or because it is raining)	*0.740*	0.264
[…] would need to develop more confidence in using the device (e.g. be convinced that I can easily reach my destination)	*0.456*	**0.663**
[…] would need to know more about the benefits of this transport mode (e.g. know how it contributes to greener mobility or improved living quality, or knowing how much time it would save me if I used it, etc.)	0.201	**0.821**
[…] would need to know more background info about how the device works. (e.g. how to charge it, how fast it goes, etc.)	0.186	**0.868**
Mean	2.861	2.843
Standard Deviation	0.999	0.938
Chronbach's Alpha	0.859	0.831

Opportunity		
	Physical	Social
[…] would have to have better maintained shared devices so that I would want to use it more (e.g. replace damaged scooters, better cleaned, etc.)	**0.731**	0.292
[…] would need to have the transport mode more accessible/available (e.g. need to have a personal device or should be able to make use of a shared device)	**0.736**	0.290
[…] would need to have more money to use this transport mode	**0.712**	0.181
[…] would need to have an adapted device in order for me to be able to use it (e.g. a different seat mounted, etc.)	**0.608**	<u>*0.436*</u>
[…] would need to have more time to use this transport mode.	**0.535**	<u>*0.348*</u>
[…] would have to have some facilities at my main activity that make it able for me to use it (e.g. ability to shower, ability to charge it, etc.)	**0.747**	0.167
[…] would have to have more support from others to use the transport mode (e.g. have friends that support me and don't laugh with me for using it)	<u>*0.315*</u>	**0.801**
[…] would need to feel that I'm part of a community (e.g. live in a city where most people use it as a transport mode as part of their life)	0.242	**0.809**
[…] would need to have more people in my close environment around me that use the transport mode (e.g. colleagues that use the transport mode, my family, my friends)	0.263	**0.827**
[…] would need to have more triggers to be prompted to use the transport mode (e.g. someone that passes me every morning and is faster at work than me, other people that use it look more healthy, etc.)	0.285	**0.748**
Mean	3.013	2.658
Standard Deviation	0.838	0.953
Chronbach's Alpha	0.831	0.868
Motivation		
	Reflective	Automatic
[…] would need to feel that it is safe to use (e.g. having read somewhere that it is a safe transport mode)	**0.612**	<u>*0.489*</u>
[…] would need to make a plan to use the transport mode (e.g. think about the alternative routes I can take, plan my trip better in advance)	**0.547**	<u>*0.579*</u>
[…] would need to feel that it is natural for me to use it (i.e. I feel bad if I am using a different transport mode, while knowing the e-scooter would have been better).	**0.348**	<u>*0.714*</u>
[…] would have to belief that I contribute to environmental sustainability (e.g. I would need to be convinced that using this transport mode is good for the environment)	**0.470**	<u>*0.574*</u>
[…] would need to get fun out of using this mode (e.g. feel happy that I don't take the polluting car or get relaxed from the morning air)	0.254	**0.795**
[…] would automatically need to feel that I want to use this mode (e.g. automatically think of using this mode since I like physical activity or like the fresh morning air, etc.))	0.254	**0.823**
[…] would have to develop a habit of using the transport mode (e.g. would need to make a habit of going with this mode to the station)	<u>*0.344*</u>	**0.752**
[…] would need to overcome negative feelings that automatically seep in (e.g. overcome the automatic thought that it is unsafe to use this transport mode, because I saw someone having an accident or falling).	<u>*0.905*</u>	0.211
Mean	3.189	3.270
Standard Deviation	0.893	0.934
Chronbach's Alpha	0.819	0.837

Items in italic and underlined loaded onto the factor but were left out due to a lower alpha value or cross loading that couldn't be explained on a factor. Bold items are part of the factor and were taken to calculate a mean score for the factor.

Vias institute

Chaussée de Haecht / Haachtsesteenweg 1405
1130 Brussels

+32 2 244 15 11

info@vias.be

www.vias.be