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Infrastructures and transportation systems

Master's Degree Thesis

Micro- mobility vehicles: current regulatory framework and possible solutions to improve safety for the road user.

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Abstract

In recent years, micro-mobility usage, such as electric bikes and electric scooters, has become increasingly popular as a mode of transport in many countries due to the introduction of shared services. Also, the purchase of micromobility vehicles has increased significantly. Electric micro-mobility vehicles are environmentally friendly, provide efficient solutions for last-mile trips, and link to major transit stations. However, due to their recent diffusion, the regulatory framework governing micro-mobility vehicles varies across different countries, and they have undergone several changes over the years. While micro-mobility vehicles offer substitution benefits to individuals, the safety concern regarding these vehicles remains controversial.

This thesis aims to analyze the existing regulatory framework governing micro-mobility vehicles, particularly electric scooters and electric bikes, in terms of technical specifications, the use of infrastructure, general rules of riding, and homologation requirements in Belgium, France, Germany, and Italy. In addition, explore the similarities and differences within the regulations in these countries. Also, the usage patterns, as well as the characteristics of e-bike and e-scooter users, are outlined in this thesis.

Furthermore, to understand the safety of micro-mobility vehicles and the key risk factors associated with e-bike and e-scooter accidents, a descriptive analysis, as well as the construction of a random forest model through R programming language is made for e-scooter accidents in France and e-bike accidents in Belgium and France. The selection of these countries in terms of analysis and modeling is merely due to the data availability. The random forest model aims to predict the severity levels of e-scooter and e-bike accidents. Additionally, it identifies the risk factors that contribute to specific accident severity by examining variables related to user and trip characteristics, infrastructure characteristics, and collision characteristics.

The results of the key risk variables that influence e-scooters and e-bike accidents provide us clear guidelines for introducing technology advancements to improve their safety. To the best of our knowledge, we suggest the implementation of an ITS system (Intelligent transportation system) on e-scooters and e-bikes, as well as smart safety equipment, including a smart helmet and a smart reflective vest.

Sommario

Negli ultimi anni, l'uso della micromobilità, come biciclette elettriche e monopattini elettrici, è diventato sempre più popolare come mezzo di trasporto in molti paesi grazie all'introduzione dei servizi condivisi. I veicoli elettrici per la micromobilità sono ecologici, forniscono soluzioni efficienti per gli spostamenti dell'ultimo miglio e si collegano ai principali hub di trasporto. Tuttavia, a causa della loro recente diffusione, il quadro normativo che disciplina i veicoli per la micromobilità varia tra i diversi paesi e ha subito diversi cambiamenti nel corso degli anni. Sebbene i veicoli per la micromobilità offrano benefici sostitutivi agli individui, le preoccupazioni sulla sicurezza riguardanti questi veicoli rimangono controverse.

Questa tesi ha lo scopo di analizzare l'esistenza del quadro normativo che disciplina i veicoli per la micromobilità, in particolare monopattini elettrici e biciclette elettriche, in termini di specifiche tecniche, utilizzo delle infrastrutture e requisiti di omologazione in Belgio, Francia e Germania. Inoltre, esplorare le somiglianze e le differenze all'interno delle normative di questi paesi.

Inoltre, per comprendere la sicurezza dei veicoli per la micromobilità e i principali fattori di rischio associati agli incidenti con biciclette elettriche e monopattini elettrici, viene effettuata un'analisi descrittiva e la costruzione di un modello a foresta casuale tramite il linguaggio di programmazione R per gli incidenti con monopattini elettrici in Francia e gli incidenti con biciclette elettriche in Belgio e Francia. La scelta di questi paesi in termini di analisi e modellazione è dovuta esclusivamente alla disponibilità dei dati. Il modello a foresta casuale mira a prevedere i livelli di gravità derivanti dagli incidenti con monopattini elettrici e biciclette elettriche esaminando variabili relative alle caratteristiche dell'utente e del viaggio, alle caratteristiche delle infrastrutture e alle caratteristiche delle collisioni.

I risultati delle principali variabili di rischio che influenzano gli incidenti con monopattini elettrici e biciclette elettriche forniscono linee guida chiare per l'introduzione di avanzamenti tecnologici per migliorarne la sicurezza. Per quanto ne sappiamo, suggeriamo l'implementazione di un sistema ITS (sistema di trasporto intelligente) sui monopattini elettrici e sulle biciclette elettriche, nonché di dispositivi di sicurezza intelligenti, inclusi un casco intelligente e un gilet riflettente intelligente.

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1. Introduction

In recent years, micromobility products such as electric scooters, electric bikes, and hoverboards have remarkably increased due to advancements in battery technology and shared services provided by several companies [1]. In addition to the shared services often provided by e-bikes and e-scooters, the trends toward purchasing micro-mobility vehicles have also grown [1]. According to figures reported in 2018, the global micromobility market reached \$3.0 billion and is anticipated to generate \$9.8 billion in 2025 [2].

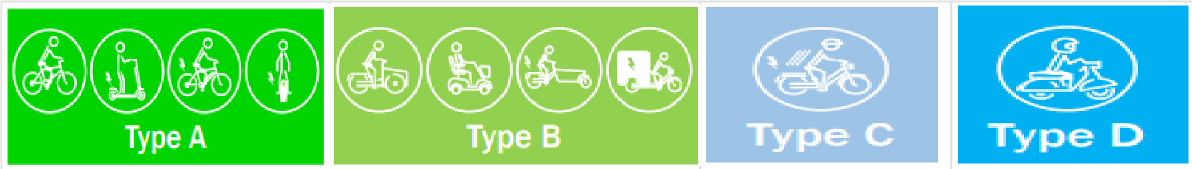
Micro-mobility vehicles increase transportation accessibility by enhancing multimodal public transit trips [3]. Moreover, several benefits are associated with the usage of micro-mobility, including reducing gas emissions, reducing traffic congestion [3], and providing mobility equity due to their lower price compared to traditional vehicles [4]. In contrast, the challenges associated with micromobility are related to infrastructure usage, changes in regulations, and safety concerns [3].

Regarding micromobility regulations, most countries that permitted the circulation of micromobility vehicles introduced their regulations between 2018 and 2020 [5]. However, in some countries, the regulatory framework governing micromobility is still under development or has exhibited several changes through the years [5]. A lack of clear regulations and standardization in micromobility products presents significant challenges for enterprises and users [5]. Such an issue is merely related to the rapid growth in micromobility usage and the increasing availability of manufacturers as well as companies that provide shared services [5].

1.1. Micromobility definition

While there is no one global definition for micromobility vehicles, the International Transport Forum (ITF) proposed the most appropriate definition in their report, "Safe Micromobility," published in 2020 [6]. ITF defines micromobility as a vehicle having a maximum design speed of 45 Km/h, a mass not greater than 350 Kg, and a vehicle's kinetic energy equal to 27 KJ [6]. Starting from this definition, ITF categorizes micromobility vehicles into four subcategories [6].

Figure 1 illustrates the comprehensive definition proposed by ITF. Type A and B include conventional bicycles and other vehicles whose electric power is cut when the vehicle reaches a speed of 25 Km/h [6]. These categories include electric bikes, electric scooters, and self-balancing vehicles [6]. Meanwhile, type C and D are often classified as moped. ITF report revealed that integrating micromobility type A in the transport system of the cities would improve road safety by decreasing the number of trips made by cars and motorcycles.



Type A: powered or unpowered vehicles weighing less than 35 kilograms and with a maximum powered design speed of 25 km/h.	**Type B:** powered or unpowered vehicles weighing between 35 kilograms and 350 kilograms and with a maximum powered design speed of 25 km/h.	**Type C:** powered vehicles weighing less than 35 kilograms and with a design speed between 25 km/h and 45 km/h	**Type D:** powered vehicles weighing between 35 kilograms and 350 kilograms and with a design speed between 25 km/h and 45 km/h.

Figure 1: definition of micromobility based on the International Transport Forum (ITF) report.
Source: The International Transport Forum (ITF) report.

1.2. Thesis objective

Our study focused on micromobility type A and, in particular, electric scooters and electric bikes in some European countries, due to their popularity both as privately owned vehicles and as shared vehicles across different European countries. EU member states do not have a standardized definition for e-scooters. However, we refer to a definition proposed by the International Transport Forum (ITF) report, which defines an e-scooter as a stand-up powered vehicle weighing less than 35 kilograms and with a maximum powered design speed of 25 km/h [6].

Regarding e-bikes, we refer to the European standard EN 15194:2017, which defines an e-bike as a bicycle assisted by an electric motor with a continuous rated power of 0.25 kW [7]. The maximum speed of such a bicycle is 25 km/h. The rated power output is cut when the bicycle reaches a speed of 25 km/h or when the rider stops pedaling [7]. Such an e-bike is called Electrically power-assisted cycle (EPACs) [7].

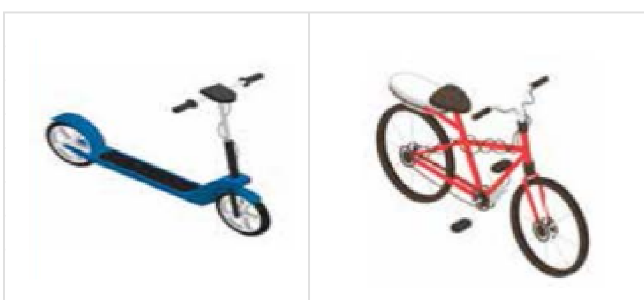


Figure 2: e-scooter and e-bike.
Source: Sandt, L., Pedestrian and Bicycle Information Center, Chapel Hill, NC.

This thesis aims to analyze the regulations governing e-scooter and e-bikes, their usage patterns, and related user characteristics in some European countries. In addition, this thesis analyses e-bike accidents in France and Belgium as well as e-scooter accidents in France by building machine learning algorithm models (random forest models) through R programming language. The purpose of the models is to understand the variables related to user, infrastructure, and collision characteristics that influence the severity levels resulting from e-bike and e-scooter accidents. The important variables resulting from the model help us introduce technological advancements to improve the safety usage of e-bikes and e-scooters.

1.3. Thesis structure

In Chapter 1, we illustrated the definition of micromobility and the related benefits and challenges for such a mode of transport. In addition, the objectives of the thesis were introduced. In Chapter 2, we explore the existing scientific literature. In Chapter 3, we analyze in detail the regulations of e-scooters and e-bikes regarding technical specifications, the use of infrastructure, and general riding rules. Furthermore, usage patterns and user characteristics were drawn.

Chapter 4 illustrates the methodology used to perform the statistical descriptive analysis for e-bike and e-scooter accidents. Additionally, the machine learning algorithm models (random forest models) help us to identify the variables that influence the severity levels of e-bike and e-scooter accidents were also introduced. Also, we perform the statistical descriptive analysis and random forest models of e-bike accidents in France and Belgium and e-scooter accidents in France. Chapter 4 was organized into three main sections: the data section. In this section, we outline the sources of the data for e-bike accidents in France and Belgium, as well as e-scooter accidents in France. In addition, we define the severity levels for road traffic accidents according to different criteria and, more in detail, the types of injuries sustained by e-scooters and e-bike users. Moreover, we perform a comparative analysis to understand the similarities and gaps between the two datasets used in this thesis. Also, a comprehensive descriptive analysis is conducted on e-bike accidents in France and Belgium and e-scooter accidents in France.

Secondly, in the method section, we define the random forest model in detail, and related techniques entail the construction of a random forest model. In addition, the necessary packages and functions that are required to be installed in the R environment to build the random forest model are explored. Also, performance measurements to validate the model performance are introduced in this section. Then, we build a separate random forest model for e-bike accidents in France, e-bike accidents in Belgium, and e-scooter accidents in France, and we validate the performance of each model.

Thirdly, in the results section, we identified the important variables that influence the severity levels of e-bike and e-scooter accidents based on the random forest model results.

In Chapter 5, we compare the safety characteristics of e-scooters and e-bikes and propose technological advancements to improve the safety of e-scooters and e-bikes. Finally, the conclusion was drawn in chapter 6.

2. Scientific literature review

This Chapter aims to review previous studies regarding the risk factors that influence the severity levels of e-scooters and e-bike accidents. Also, this Chapter reviews previous modelling approaches used to identify the factors contributing to specific severity levels of accidents.

Due to their recent establishment as a mode of transport, several studies have been conducted to analyse and model the risk factors associated with e-bike and e-scooter accidents. Most previous studies examined the influence of user, infrastructure, and collision characteristics on the accident's severity levels. Nevertheless, the amount of research is less compared to other modes of transport, such as motor vehicles.

2.1. Methodological approaches

Statistical modelling was used for a substantial amount of time because it provides reliable results on accident likelihood with decent interpretability [8]. However, predetermined relationships between dependent and independent variables and specific assumptions about the underlying data distribution are necessary for statistical modelling.

Quan Yuan et al. developed a statistical logit model to understand the factors that influence the severity levels of e-bike accidents in Beijing, China. 150 observations recorded between 2009 and 2015 were utilized to build the logit model [9]. The severity levels (dependent variables) were categorized into two classes (fatal and non-fatal), while the independent variables were related to user sociodemographic characteristics and infrastructure characteristics [9].

Paola Longo et al. use a logit model to identify the factors affecting the severity levels of e-scooter accidents in Bari, Italy [10]. The data used in developing the model was obtained from the local police records between July 2020 and November 2022. In this period, 257 e-scooter accidents were reported [10]. The severity levels (dependent variables) resulting from e-scooter accidents were categorized as follows: injury severity (No, Yes) [10]. While the independent variables were related to user and trip characteristics, road characteristics, and collision characteristics [10].

Additional types of modelling, which were observed in the literature, but fewer compared to statistical modelling, were identifying the severity levels of micro-mobility accidents using a machine learning algorithm. Almudena Sanjurjo-de-No et al. utilized the random forest machine learning algorithm to build a model to analyse and predict injury severity in single micro-mobility accidents [11]. The study analysed 6030 single micromobility accidents in Spanish urban areas from 2016 to 2020 [11]. The dependent variables were accident severity levels (serious and fatal) and (minor) [11]. The independent variables were related to users, trips, infrastructure, and collision characteristics [11].

2.2. Factors influencing e-bike and e-scooter accidents

2.2.1. User and trip characteristics

Rider and trip characteristics can provide valuable insights for urban planners and healthcare systems by identifying the risks related to users and addressing the proper policies that can cope with these risks [12]. User and trip characteristics for individuals who experienced e-bike and e-scooter accidents are usually identified in the literature by gender, age, the usage of safety equipment, trip purpose, and day/time of the trip.

Regarding gender, several studies show gender variability in the number of e-scooter and e-bike accidents as well as the severity levels. In most cases, males have experienced severer accidents compared to females [9], [10], [11], [13]. The gender variability in the number of accidents is associated with usage patterns since males use e-scooters and e-bikes more than females. Several studies associated the likelihood of experiencing e-scooter accidents with users under the age of 30 years [10], [13], [14], [15]. Regarding safety equipment, helmets are proven to be an effective preventive measure in reducing the severity of accidents [16], [17].

Concerning trip characteristics, a study conducted by Almudena Sanjurjo-de-No et al. revealed that the severity levels resulting from micromobility (bicycle, e-scooter, and other types of micro-mobility) accidents increase during leisure trips [11]. Also, the same study found that accidents were more severe from sunrise to 2 p.m. [11]. Other studies revealed that the fatalities from e-bike accidents were more frequent between 7 a.m. and 6 p.m. [9], [18]. The temporal distribution of the frequency of e-bike and e-scooter accidents occurrence can be associated with usage patterns.

2.2.2. Infrastructure characteristics

Infrastructure characteristics are also crucial in improving safety by designing appropriate geometry adjacent to the rules governing the use of the infrastructure and applying interventions for existing infrastructure. The infrastructure characteristics usually indicated in the existing literature encompass road characteristics, including the type of road, the number of lanes, and the maximum allowable speed on the road. Additional characteristics were also outlined, such as accidents occurring on sidewalks.

Micromobility users, in general, tend to sustain severe injuries when high speed is involved [11]. Moreover, Cicchino et al. observed that nearly 60% of 105 e-scooter injuries were on sidewalks [19]. Regarding road characteristics, previous study showed that e-scooter users are more likely to experience an accident on divided roads. The study associated this with users' behaviour as e-scooter users attempt to increase their speed on divided roads [10].

Huang et al. and Bai et al. studied e-bike accidents in signalized intersections [20], [21]. Both studies found that the conflict rate for e-bikes is greater than for conventional bicycles regardless of whether fault lies with the e-bike rider or the conventional bike rider [20], [21]. In addition, Liang et al. have found that the possibility of conflict between e-bike users and pedestrians on cycle paths and sidewalks is higher than that of conventional bicycles [22]. Further study revealed that 32% of the e-bike fatal accidents occurred at roadway sections and 19% at intersections [18].

2.2.3. Collision characteristics

The collision characteristics resulting from micromobility accidents include collision types such as side, rear, frontal, head-on, angle, and fall. In addition, the object involved in the accident whether it is stationary or moving objects are also outlined in the literature. Several studies analyze the collision characteristics resulting from e-bikes and e-scooters.

Regarding e-scooter collision type, angle collisions at the intersection accounted for the highest number of e-scooter accidents [10]. Concerning moving objects involved in e-scooter accidents, a study conducted by Tommaso Scquizzato et al. analyzed the road traffic accidents involving standing electric scooters reported in newspapers in Italy revealed that e-scooter accidents involving passenger cars accounted for 50% of severe accidents [13].

In the case of e-bike accidents, Linjun et al. and Quan Yuan et al. found that accidents involving passenger cars accounted for most of e-bike fatal accidents [9] [18]. Also, Linjun et al. revealed that angle collision was responsible for 55% of e-bike accident fatalities [18].

In summary, few studies have examined the three major contributing factors influencing the severity levels of e-bike and e-scooter accidents through machine learning algorithm models. Additionally, based on the modelling results, there is a gap in addressing technological advancements to improve the safe usage of micromobility, particularly e-bikes and e-scooters. Therefore, this study thoroughly examines the severity levels of e-bike and e-scooter accidents. Additionally, it investigates the factors influencing severe accident outcomes through a machine learning algorithm (Random Forest); this helps us address the proper technology advancement to improve safe usage.

3. Micro-mobility usage in some EU countries and related regulatory framework

In recent years, micro-mobility technologies have grown significantly in Europe [23]. Nevertheless, European standardization bodies still need to reach unified safety standards regarding micro-mobility [23]. According to the European Commission, the safety challenges related to micro-mobility and its rapid increase highlight the need for more effort in sharing knowledge, practices, and guidance [24]. The regulatory frameworks in the domain of micro-mobility within EU member states include several legal provisions, national regulations, local regulations, technical standards, EU directives, and assessments of market accessibility [25]. This Chapter explores these combinations for some EU member states, focusing mainly on e-scooters and e-bikes. In addition, it analyses e-scooter and e-bike regulations regarding vehicle's technical specifications, the usage of roads, and market accessibility in terms of homologation requirements. Also, the general riding rules will be explored to understand the similarities and differences between the targeted countries in our study.

Regarding technical specifications, this Chapter investigates the following aspects: the vehicle's dimensions, overall vehicle weight, braking system specifications, lighting system specifications, and continuous rated power. These technical specifications are necessary for vehicle type approval within the EU single market and in determining how vehicles are categorized for use on EU roads. Furthermore, given their significant effects on road safety, the regulations concerning the use of infrastructure are essential to be taken into account in our study. Typically, these regulations are outlined in the national traffic law and include rules such as speed limits of the vehicles, road usage, minimum age of riding, and the use of safety equipment.

3.1. Electric Scooters usage in some EU countries and related regulatory framework

Now, we focus on e-scooters, which are becoming commonly used in some European countries also due to the introduction of shared e-scooters since 2018 [23]. Also, e-scooter ownership has increased significantly. However, data concerning e-scooter ownership across many European countries are scarce. Nevertheless, in 2022 figures from France displayed that more than 700,000 e-scooters have been sold to private citizens [26]. Also, in the UK, the cumulative imports by November 2022 exceeded 1.3 million units [23].

The (EU) No 168/2013, dealing with the approval and market surveillance of two- or three-wheel vehicles and quadricycles, did not consider the electric scooter [27]. However, the European Committee of Standardization developed the standard for Personal Light Electric Vehicles (PLEV), the EN 17128:2020 [23], a voluntary standard that includes information related to e-scooter technical specifications. Such Standards have been implemented by some European countries; for instance, Spain's General Directorate for Traffic approved a manual of characteristics of the vehicles of personal mobility, which included elements from EN 17128:202 [23] such as specifications for lighting and electrical components, a minimum wheel size of 203.2mm (8 inches) requirement, and the addition of anti-tampering features [23]. Table 1 provides an overview of e-scooters in some European countries targeted in our study regarding permissions for e-scooter circulation and homologation if required. The first three countries presented in Table 1 are covered in details while for Italy we summarized the regulations in Appendix A, Table 29.

Country	Name	E-scooters permitted?	homologation
Belgium	Trottinette électrique / Elektronische autoped	Yes	No
France	Trottinette électrique	Yes	No
Germany	Elektrokleinstfahrzeuge	Yes	Yes
Italy	Monopattini elettrici	Yes	No

Table 1: permission for e-scooters circulation and homologation.
Source: ETSC, the European Transport Safety Council.

3.2. E-scooter regulatory framework, usage and accidents patterns in Belgium

3.2.1. E-scooter regulatory framework in Belgium

The Belgian Traffic law has established two distinct categorizations for personal vehicles: non-motorized transport vehicles are any vehicle that can move by muscular force and is not equipped with an engine, including skateboards, wheelchairs, and scooters [28]. On the other hand, motorized transport includes any motor vehicle with one wheel or more and whose maximum speed is limited to 25 km per hour, such as electric wheelchairs, Segways, electric scooters, and monowheels [28].

Over the years, the e-scooter regulations in Belgium experienced several modifications. The Belgian authorities provide the regulations concerning the use of e-scooters as part of the traffic law (Code de la Route), laying down technical requirements, the use of roads, and general riding rules regarding e-scooters. It is crucial to note that e-scooter users are considered cyclists; therefore, most regulations applicable to cyclists also apply to e-scooter users [28]. The comprehensive regulations in Appendix A, Table 26 are sorted from the Belgian traffic law (Code de la Route) [28] and ETSC, the European Transport Safety Council. They concern technical vehicle specifications, the use of roads, and general riding rules.

Belgian law provides certain technical specifications for e-scooters concerning geometry. However, it does not provide detailed information regarding vehicle geometry. It only indicates the maximum width, which is 1 meter [28]; this can ensure that users can safely navigate through traffic areas. However, it also lacks information regarding height and length, which is crucial for stability. Concerning the braking system; the Belgian traffic law mentions the braking system in general terms, and it needs to go into better depth about the proper barking test, which can be considered a lack of precision within the technical specifications. The Belgian traffic law indicates only the need for an adequate braking system which allows users to stop their e-scooters safely [28].

Visibility is also crucial to ensure safe riding. Therefore, the Belgian regulations indicated that all e-scooters must be equipped with front and rear reflectors, a white front light, and a red rear light, which can warn other road users of e-scooters at nighttime [28]. Additionally, an audible warning device such as a bell is mandatory to notify pedestrians and other road users. Regarding continuous rated power, the Belgian regulation did not indicate a specific rate in Kw; no such information is present in all Belgian traffic laws [28].

Concerning the use of infrastructure, Belgian traffic law considers e-scooter users to be cyclists. Hence, they are obligated to use cycle paths whenever they are present on public roads [28]. In the absence of cycle paths, they can use the public road with a speed limit of 50 Km/h or less [28]. However, they should ride to the right side in relation to the direction of their travel and prioritize users who follow these parts of the public road [28]. In addition, road shoulders and parking lanes can be used by e-scooter users, as well as sidewalks outside build-up areas [28]. However, it is important to note that the use of sidewalks is permitted outside built-up areas; it is prohibited in built-up areas [28]. However, on sidewalks within built-up areas, users must walk alongside their e-scooters while holding them by hand [28]. Access to highways is strictly prohibited [28].

Other rules presented in Appendix A, Table 26 that largely influence e-scooter safety and responsible use are the following: the maximum speed is 25 km/h, riders must be 16 years old and are prohibited from carrying passengers [29]. Like motorized vehicles, e-scooter users are subject to a drink-driving limit and a ban on phone use while riding [29]. While helmets and vehicle insurance are not mandated by law, they are strongly recommended for optimal protection [29].

3.2.2. E-scooter usage in Belgium

The usage of e-scooters on Belgian roads has remarkably increased after the establishment of shared e-scooter services [30]. Although privately owned e-scooters are commonly used in Belgium, the data and information about user characteristics are scarce compared to shared e-scooters. Therefore, we refer to data from shared e-scooters in order to understand the usage and related user characteristics.

To explore the user characteristics, we refer to the Brussels Regional survey, which was performed by Brussels Regional Public Services – Mobility Brussels [31]. The survey aimed to understand the factors that affect the use of shared micro-mobility, such as non-electric bikes, e-bikes, and e-scooters. Two thousand four hundred-eleven users participated in the online survey, which was conducted between May 11 and November 30, 2023 [31]. The survey offered available insight into the sociodemographic characteristics of e-scooter users [31].

The first findings from the survey have shown interesting patterns concerning shared e-scooter users [31]. They are mainly young, male, employed, and have completed long studies [31]. Also, most of the usage was in urban areas [31]. Shared e-scooters were the second most used mode of shared micromobility [31]. Furthermore, out of 2,411 participants 13% were e-scooter users, 61% were under 35 years old, 18 % were between the ages of 35 to 44 years, and 21% were above 45 years old. Also, 74% of the users were males [31].

3.2.3. E-scooters accidents in Belgium

Given the recent arrival of electric scooters on Belgian roads, the knowledge of their accident history is still fragmentary [30]. Nevertheless, the national statistical office Statabel provides information on e-scooter accidents at the national level depending on police records [30]. Notice that the police accidents recording tools have been able to distinguish between non-motorized and motorized travel vehicles since 2016, and more specifically, electric scooters since 2019 [30].

Figure 3 illustrates the number of e-scooter accidents occurred in Belgian provinces between 2019 and 2021[30]. The map shows that Brussels experienced the highest number of accidents accounting for 722 accidents, followed by Antwerp with 403 accidents, East Flanders experienced 149, West Flanders 81, and Luxembourg had the lowest number with only 7 accidents [30]. The cumulative accidents in the other provinces accounting for 206 [30].

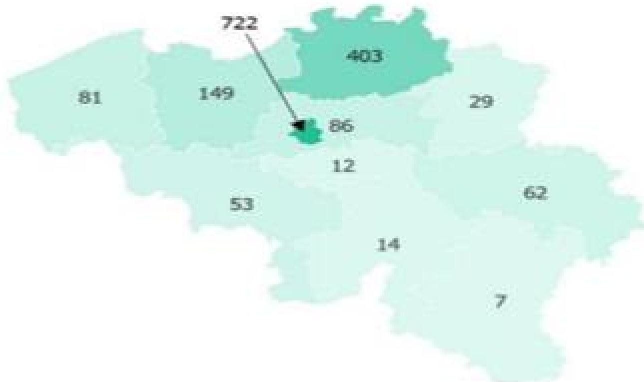


Figure 3: number of e-scooter accidents occurred in Belgian provinces between 2019 and 2021.
Source: Statbel (Directorate General Statistics – Statistics Belgium).

Figure 4 shows the distribution of e-scooter accidents regarding land use patterns; most accidents occurred in urban areas, accounting for 89%, while only 8% occurred in extra-urban areas. The concentration of e-scooter accidents was observed in major cities [30]. 45% of scooter accidents occurred in the Brussels-Capital Region and 19% in Antwerp. This variety of accidents between urban and extra-urban areas is merely due to the limited availability of e-scooters outside these metropolitan cities [30] and due to the high usage patterns of shared e-scooters in urban areas compared to extra urban areas as previously mentioned by Brussels Regional survey [31].

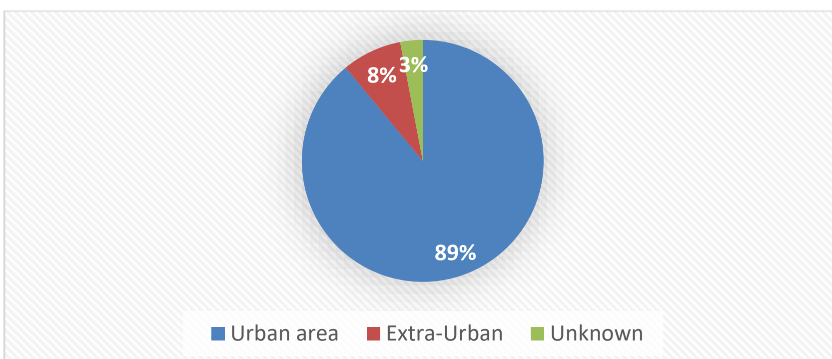


Figure 4: Percentage of e-scooters accidents with injury depending on location (2019- 2021).
Source: Statbel (Directorate General Statistics – Statistics Belgium).

Regarding victim's demographic characteristics, e-scooter accidents in Belgium revealed correlations between users' age and the frequency of accident occurrence; two-thirds of the users involved in the accidents were under 35 years old [30]. In addition, gender variability was observed within the number of accidents; males experienced more accidents than females. The figures revealed that approximately 2.3 males were involved in e-scooter accidents for each female [30]. The findings from the e-scooter accidents data related to the usage patterns and the accidents results can be reasonable since males are using more e-scooters than females, as revealed by the Brussels Region results, which were previously mentioned [31]. Moreover, the fact that two-third of users who involved in e-scooters accidents are under 35 years old are aligned with the same survey which revealed that 61% of the shared e-scooters users were under 35 years old this also can be linked to the usage patterns [31].

Figure 5 shows e-scooter accidents by collision type between 2019 and 2021 on Belgium roads [30]. 56% of the accidents involved passenger cars, highlighting the potential for conflicts between cars due to shared road space [30]. Pedestrians were involved in 7%, the conflicts between e-scooter users and pedestrians can be linked to the fact that, until July 2022, according to Belgian regulations, e-scooter users were permitted to ride on the sidewalks [32]. Interestingly, 17% of accidents with no collision [30] are related to users dismissing their e-scooters before the accident. The remaining accidents were distributed among cyclists 9%, vans 4%, mopeds 2%, and other collisions 5% [30].

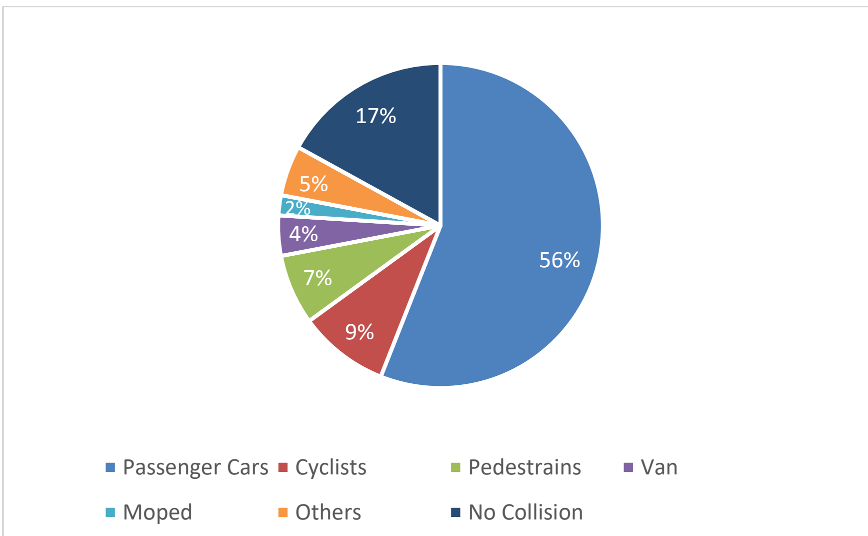


Figure 5: Percentage of e-scooters accidents with injury by vehicle involved.
Source: Statbel (Directorate General Statistics – Statistics Belgium).

3.3. E-scooter regulatory framework, usage and accidents patterns in France

3.3.1. E-scooter regulatory framework in France

The French regulations define an e-scooter as a motorized personal transport vehicle EDPm (Engin de déplacement personnel motorisé), a vehicle without a seat made exclusively for one person's use. It is not equipped with a thermal engine or thermal assistance [33]. Such a vehicle's maximum speed is equal to 25 km/h [33]. Like the Belgian traffic law, the French traffic law makes distinction between motorized and non-motorized personal travel vehicles. Non-motorized vehicles, requiring muscular power for propulsion, differ significantly from motorized vehicles equipped with electric motors [33].

The official French regulations were approved immediately after the legalization of e-scooters in October 2019 through the issuance of Decree No. 2019-1082 in the French traffic law (Code de la route) [33]. The French traffic law, in general, provides regulations on the policing of road traffic and the use of public roads. The comprehensive regulations in Appendix A, Table 27 are sourced from French traffic law (Code de la route), the official journal of the French Republic, and ETSC (The European Transport Safety Council). From these three sources, we extracted a complete picture of the regulations concerning e-scooters technical specifications, the use of roads, and general rules of riding.

To begin with e-scooter's technical specifications, the French traffic law has set limitations for e-scooter dimensions: the maximum width must not exceed 0.9 meters, and the length must not exceed 1.65 meters [33]. Nevertheless, the technical specifications lack information regarding the vehicle's height and weight. Also, visibility during nighttime is a crucial aspect that influences e-scooters safety. Thus, the regulations highlight information regarding the lighting system: e-scooters must have front, rear, and side reflectors, as well as front and rear lights [33]. Notably, the regulations do not mention any requirements for continuous rated power [33]. Moreover, e-scooters must have an audible warning device controlled from the handlebars as well as safe braking (hand or foot controls). In addition, to ensure an effective stopping e-scooter must pass the braking test, which is provided in Appendix C [33].

Regarding the use of roads, e-scooter riders must use cycle lanes within urban areas; however, in the absence of cycle lanes, riding on roads with a speed limit of 50 km/h or less and on paved shoulders is allowed [33]. Similar rules outside urban areas, except that e-scooters may also be allowed on some roads with a maximum speed limit of 80 km/h; however, riders must wear a helmet and reflective vest [33]. Using the sidewalks for parking is permitted [33]. Nevertheless, local authorities may impose restrictions. Importantly, riding e-scooters on sidewalks is strictly prohibited [33].

In addition, the general rules of riding that are presented in Appendix A, Table 27 are the following: the maximum speed is 25 km/h, and the minimum age for riding is 14 years old [33]. Regarding the use of safety equipment, wearing a reflective vest is compulsory when riding on roads with a speed limit of 80 km/h. However, wearing a helmet is not compulsory but is highly recommended [29]. Moreover, e-scooter users are obligated to have civil liability insurance to cover any property damage that can result from an accident [33]. Additionally, dual riding is not allowed, as well as riding under the influence of alcohol [29].

3.3.2. E-scooter usage in France

The national plan to better regulate e-scooters, which was published in March 2023, have revealed significant increase in the use of e-scooters in France [26]. Approximately 2.5 million of the people in France owned e-scooters. Also, the average daily trips by shared e-scooters reached 10,000 trips [26]. One-third of people who live in France use or have used an e-scooter occasionally or daily, particularly in home-work trips [26]. Around 60% of e-scooter users ride inside the city that they live in [34]. In terms of the usage inside the cities, before September 2023 Paris has the highest usage of shared e-scooters, making it the top city for this mode of transport [35]. In addition, e-scooters often combine with other modes of transport. According to these figures, we can observe that the use of e-scooters among French residents is becoming increasingly popular as a mode of transport.

Regarding user's characteristics, we refer to a face-to-face road survey conducted in Paris, between (May – June 2019) among e-scooter users with 459 participants [36]. The characteristics of the participants were the following: 2/3 were males, 1/3 were females, 93% were users of shared e-scooters, and 7% were owners of e-scooters [36]. The survey findings revealed that e-scooter users in Paris during the study period were predominantly young males accounting for 70% and 85% were under 35 years old [36].

3.3.3. E-scooters accidents in France

The safety concerns towards e-scooters have always been a controversial issue. For instance, in April 2023, and as response to the increased number of e-scooters accidents in Paris, the decision makers in Paris held a referendum towards the use of shared e-scooter [37]. Nearly to 90% of Parisians voted to ban shared e-scooters [37].

Since the permission of e-scooters circulation in 2019, the number of injuries resulting from e-scooter accidents has rapidly increased over the years, in line with their usage. The French Academy of Medicine reported an increase of 180% in 2022 compared to 2019 [23]. As previously mentioned, The French traffic law categorizes e-scooters as motorized personal travel vehicles. Thus, data concerning e-scooter accidents did not distinguish e-scooter accidents from other motorized personal travel vehicles.

Figure 6 shows the number of motorized personal transport vehicle accidents that occurred between 2019 and 2022 in different regions of France. Île-de-France reported the highest number of accidents, with 2777. However, we can see the differences in the number of accidents between the Île-de-France region and the Auvergne-Rhône-Alpes region, which reported the second-highest number of accidents, with 740. This variation in the number of accidents is related to the highest number of accidents in Paris in the same period.

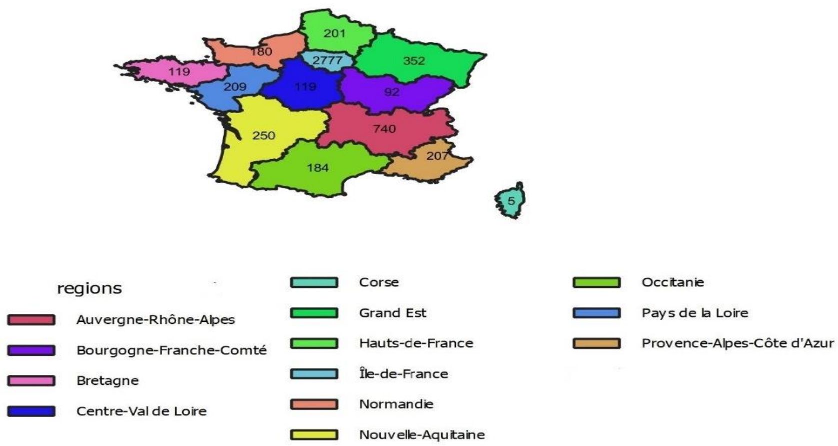


Figure 6: the distribution of motorized personal transport vehicles in some French regions between 2019 to 2022- from QGIS 3.28.3 Firenze.
Source: ONISR the National Interministerial Road Safety Observatory (Observatoire National Interministériel de la Sécurité Routière).

E-scooter accidents are more likely to occur in urban areas than extra-urban areas. Figure 7 shows the percentage of e-scooters accidents in France based on land use patterns 97% of e-scooter accidents in France occurred in urban areas [38], [39], [40], [41] merely concentrated in the city this correlated to the fact that approximately, 60% of e-scooter users ride inside the city that they live in [34]. Also, this is due to the availability of shared e-scooters in the cities.

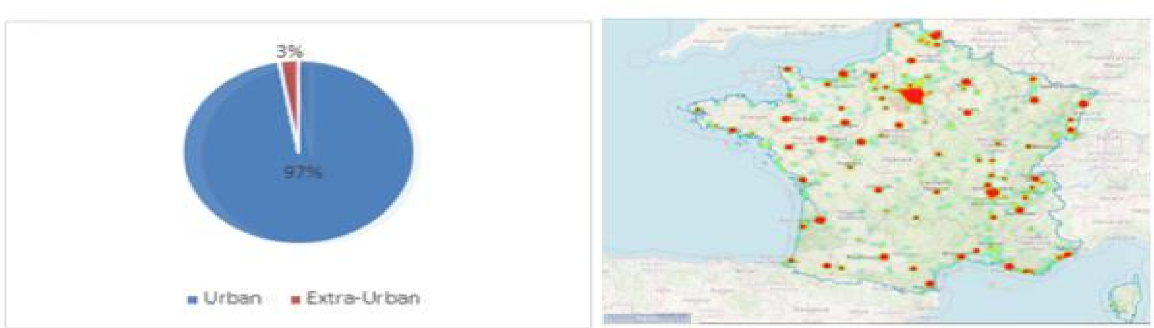


Figure 7: percentage of motorized personal travel devices accidents in France by land use patterns.
Source: ONISR

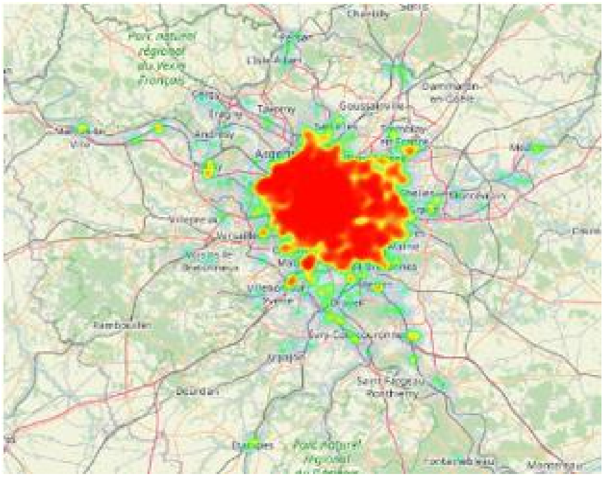


Figure 8: distribution of motorized travel vehicle accidents in Île-de-France region.
Source: ONISR

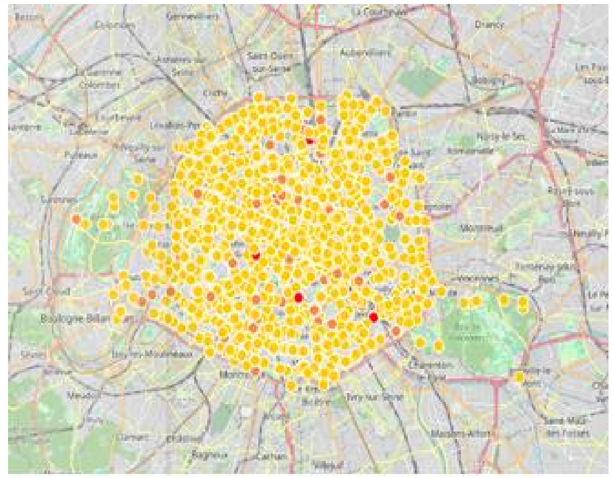


Figure 9: distribution of motorized travel vehicles accidents in Paris.
Source: ONISR

Figure 8 illustrates the distribution of e-scooter accidents in Île-de-France region while Figure 9 shows the concentration of e-scooter accidents in Paris. These variations in the number of accidents can be correlated to the highest usage of e-scooter in Paris as previously mentioned. Also, it can justify the ban on shared e-scooters that was implemented in Paris in April 2023.

As shown in Figure 6, Grand Est as a region experienced 352 accidents, and Nouvelle-Aquitaine follows closely with 250 accidents. Hauts-de-France reported 201 accidents, while Provence-Alpes-Côte d'Azur and Pays de la Loire reported 207 and 209 accidents, respectively, showing relatively similar figures. Occitanie and Normandie had 184 and 180 accidents, respectively. Bretagne and Centre-Val de Loire both reported 119 accidents each. While Bourgogne-Franche-Comté reported 92 accidents, Corse as a region experienced the lowest number of accidents, with only five.

Regarding victim demographic characteristics, males experienced more accidents than females [38], [39], [40], [41], and this can be related to usage patterns that we previously mentioned in a face-to-face road survey conducted in Paris, between (May – June 2019) [36]. The survey revealed that e-scooters users in Paris were predominately males and young with high educational background. Moreover, two-thirds of users who experienced e-scooter accidents with injuries between 2019 and 2022 were under 35 years old [38], [39], [40], [41]. This finding also related to the usage patterns indicated by the survey, which was previously mentioned [36].

3.4. E-scooter regulatory framework, usage and accidents patterns in Germany

3.4.1. E-scooter regulatory framework in Germany

E-scooters were legally admitted to German roads on June 15, 2019, with the introduction of the Small Electric Vehicle Regulation (Elektrokleinstfahrzeuge-Verordnung [eKFV]) [27]. The German traffic regulation defines e-scooters as small electric vehicles with a maximum design speed of not less than 6 km/h and not more than 20 km/h [42].

Appendix A, Table 28 provides a comprehensive picture of the regulations governing the usage of e-scooters on German roads. The regulations are sourced from the Small Electric Vehicle Regulation (Elektrokleinstfahrzeuge-Verordnung [eKFV]), the German Road Traffic Regulations (Straßenverkehrs-Ordnung [StVO]), the German Road Traffic Licensing Regulations (Straßenverkehrs-Zulassungs-Ordnung [StVZO]), and ETSC (The European Transport Safety Council). The table contains regulations concerning e-scooter technical specifications, infrastructure use, and general riding rules.

Regarding technical specifications, the German regulation provides more detailed information compared to Belgian and French. The eKFV provides detailed specifications concerning vehicle dimensions with a handlebar of at least 700 mm, a total width of not more than 700mm [42]. a total height of not more than 1400 mm, and a total length of not more than 2000 mm [42]. A maximum vehicle mass of no more than 55 kg does not include the driver's weight [42]. In addition, the continuous rated power for the electric motor is not more than 500 watts [42]. Also, e-scooters must be equipped with warning sounding bells, which must comply with the Road Traffic Licensing Regulation (StVZO) [42].

E-scooters must be equipped with two independent brakes; the brake system must be able to stop the e-scooter effectively at maximum speed [42]. They must achieve a deceleration value of at least 3.5 m/s² [42]. If one brake fails, the other should still provide a minimum deceleration of 44% of the required braking effect without causing the vehicle to leave its lane [42]. Moreover, the braking system must comply with the braking test indicated in Appendix C [42]. The e-scooter must be equipped with lighting and signalling equipment to comply with the Road Traffic Licensing Regulation (StVZO) as indicated in Appendix A, Table 28 [42].

Regarding infrastructure use, e-scooter users are obliged to use cycle paths in buildup areas. In the absence of cycle paths, they can ride on roads [42]. The same applies when riding outside buildup areas, but in such cases, e-scooter users can also ride on road shoulders [42]. However, the use of motorways and sidewalks is strictly prohibited.

Further regulations are presented in Appendix A, Table 28: the maximum speed of an e-scooter is 20 km/h, the use of a helmet is not mandatory, and the minimum age for riding an e-scooter is 14 years [29]. Moreover, e-scooter users must have a valid insurance to cover the property damage resulting from an accident [29]. Also, dual riding is not allowed. The minimum alcohol drink limit is 0.5‰ and zero for those under 21 [29].

Finally, it is worth mentioning that, according to German regulations, e-scooters are given the same type of approval as motor vehicles [43]. Therefore, for e-scooters to be used on German roads, the implementation of homologation is compulsory [43]. Manufacturers who are willing to sell their e-scooters in Germany must get a homologation certificate. The Federal Motor Transport Authority (Kraftfahrt-Bundesamt [KBA]), upon manufacturer request (KBA), will provide a homologation certificate after verifying that the e-scooter meets the technical requirements presented in Appendix A, Table 28 [43].

3.4.2. E- scooter usage in Germany

Germany attempted to control the release of e-scooters compared with previously mentioned countries [44]. Even though Germany is one of the recent European countries to emerge with e-scooters as one of its transportation systems. The usage of e-scooters, and in particular, the shared e-scooter services, has greatly increased in most German cities recently after the approval was issued, surpassing other European countries [45].

As in the case of France and Belgium, data concerning e-scooter ownership are scarce. Therefore, we refer to data from e-scooter-shared services to understand the usage of e-scooters and related user characteristics. In 2023, figures have shown that approximately 11 million shared users have used e-scooters, making Germany the leading e-scooter-sharing market in Europe [46].

Regarding e-scooter users' characteristics, since insuring e-scooters is mandatory in Germany, we refer to figures from insured e-scooters [46]. According to insurance companies, e-scooter ownership exhibited gender variability in 2022; nearly three-quarters of insured e-scooters were owned by males [46]. In addition, e-scooter users between the ages of 30 and 39 years were observed to be the largest age group in owning e-scooters [46].

3.4.3. E- scooter accidents in Germany

In 2021, after e-scooters became commonly used in major cities in Germany, the German Federal Statistical Office (Destatis) released a press to understand the accident patterns related to e-scooters based on accident data from 2020 [47]. The number of injuries experienced by e-scooter users in 2020 was 2,155. Most of the accidents with personal injuries occurred in densely populated federal states [47]. North Rhine-Westphalia (566) and Bavaria (334), while the fewest injuries were reported in Mecklenburg-Western Pomerania (16) and Thuringia (11) [47].

Regarding victim characteristics, the press has shown that users of different ages experienced e-scooter accidents [47]. However, most victims were under 45 years old, accounting for (76%) and (34%) were even younger than 25 years. In contrast, only (7%) of the victims were above 65 years old [47]; this variability in e-scooter accidents can be associated with usage patterns. As mentioned in the previous section, e-scooter users were predominantly under the age of 40 years old.

Concerning collision characteristics, out of the 2,155 e-scooter accidents, 918 were accidents without collision, meaning that no other road users were involved in the accident [47]. This may be related to e-scooter users often abandoning their vehicles before the accident [47]. In addition, more than half (1,170) of the e-scooter accidents resulting in personal injury involved a second road user, mostly passenger cars [47].

3.5. Comparison of e-scooter regulatory framework in some EU countries

Regulatory framework	Belgium	France	Germany	Italy
Maximum width (m)	1	0.9	0.7	0.75
Maximum Length (m)	N/A	1.65	2	2
Maximum Height (m)	N/A	N/A	1.4	1.5
E-scooter mass (Kg)	N/A	N/A	55	40
Braking test	Not required	Required	Required	Not required
Continuous rated power (Watt)	N/A	N/A	500	500
Max speed (Km/h)	25	25	20	20
Min age	16	14	14	14
Drink limit	Same as car	Not allowed	Same as car	N/A
Mandatory Helmet	No	No	No	< 18 years
Mandatory insurance	No	Yes	Yes	No*
Dual riding	Not allowed	Not allowed	Not allowed	Not allowed
Ride on sidewalk	Not allowed	Not allowed	Not allowed	Not allowed
Riding on cycle path	Yes	Yes	Yes	Yes
Roadway usage Road with max speed limit of (Km/h)	50	50	50	50

Table 2: comparison of e-scooter regulation in some European countries.

Table 2 illustrates the variability in the regulatory frameworks for e-scooters across some European countries, including Belgium, France, Germany, and Italy. The differences in the regulations might be associated with the recent establishment of these regulations. In most European countries where e-scooters are permitted to circulate, the regulations came into force between 2019 and 2020. Table 2 shows notable differences in the technical specifications, including vehicle dimensions, maximum continuous rated power, and braking test obligation. Germany and Italy provide detailed requirements concerning the vehicle's weight and dimensions, whereas the regulations in Belgium and France lack specific details on maximum length and vehicle mass. Additionally, the French and German regulations require manufacturers to perform braking tests to validate the effective stopping performance of the vehicle. At the same time, the braking test requirement is not found in the Italian and Belgian regulations.

There is minimal difference among the countries studied regarding infrastructure use and general riding rules. The above-mentioned countries instruct e-scooter users to use cycle paths. In the absence of cycle paths, e-scooters are allowed to use the road with a maximum speed limit of 50 km/h. However, in France, e-scooter users may also use roads with a maximum speed limit of 80 km/h outside urban areas, but they must wear a reflective vest and helmet. Moreover, in the countries targeted in our study, riding e-scooters on sidewalks is prohibited.

Concerning the general rules for riding, the minimum age for riding e-scooters is 14 years old, except for Belgium, which is 16 years old. In addition, wearing a helmet is not mandatory only in Italy for users under 18 years old. For alcohol, it is forbidden to ride an e-scooter under the influence of alcohol in France, while in Germany and Belgium, the limit is set as in the case of cars. Finally, insurance to cover the property damage resulting from e-scooter accidents is mandatory in France and Germany, while it is not obligated in Belgium; however, in Italy, it is mandatory only for e-scooter sharing services providers.

3.6. Electric Bike usage in some EU countries and related regulatory framework

Now, we focus on e-bikes; In recent years, e-bikes have significantly gained popularity in the European bicycle market [46]. The trend towards electric bicycles has directly affected the price, the people who buy them, the average cost, and the maintenance within the European single market [46]. For instance, in Germany and the Netherlands, the number of electric bicycles that have been sold represents more than 50 % of the quota of the bicycle market each year [46]. Germany is leading the electric bicycle market, with 2.1 million e-bikes sold in 2023 [46].

As previously mentioned in Chapter one, there are different types of electric bicycles that are operating on European roads; however, in our study, we focus only on the EPACs due to the rapid boom of this type of electric bicycle [46]. For instance, in the Netherlands, the sales of EPACs dominate the bicycle market, overcoming all other types of electric bikes [46]. Because EPACs dominate the electric bicycle market, the term e-bike is often used to refer exclusively to EPACs [46] which has the following definition as indicated in Chapter one: bicycle assisted by an electric motor with a continuous rated power of 0.25 kW. The maximum speed of such bicycle is 25 km/h; therefore, the output of the rated power is cut when the bicycle reach speed of 25 km/h or when the rider stops pedalling [46]. In this study, when we refer to e-bikes, we mean EPACs. Since there is no huge difference in the regulations governing e-bikes across EU countries, in our study we referred only to three countries (Belgium, France, and Germany).

The perspective that older adults can prefer e-bikes due to the support they can gain from the electric motor while riding is not valid in some countries, where the typical e-bike users' age group is between 25 and 34 years [46]. However, in some countries like Poland, which has numerous frequent cyclists, the usage of e-bikes is also common among people aged between 35 and 54 years [46].

3.7. E-bike regulatory framework in EU countries

The type of approval laid down in Regulation EU No 168/2013 is applied to all types of electric bicycles except EPACs [48]. The European standard EN 15194 (EPAC – Electrically Power Assisted Cycles) has been adopted for this type of electric bicycle [48]. This standard provides several technical specifications. For instance, concerning mechanical specifications, EN 15194 set limitations for the handlebar dimensions, tiers, tire inflation, and additional mechanical specifications. Besides the mechanical specification, EN 15194 indicates several requirements for batteries, braking systems, lighting systems, and related quality tests. However, most of EU members have implemented such standards [48]. E-bike manufacturers who are targeting the EU market must comply with several directives, which are the following:

1- General Product Safety Directive 2001/95/EC

Manufacturers attempting to sell their e-bikes in the EU must apply the General Product Safety Directive 2001/95/EC instructions [48]. This directive must be applied to ensure that e-bikes provided by manufacturers in the EU market are safe [48].

2- Electromagnetic compatibility directive (EMC directive)

Interference between electronic devices might occur when such devices are near each other [48]. The objective of complying with the EMC directive is to limit these interferences and put them under reasonable control [48].

3- RoHS directive (Directive 2011/65/EC)

The objective of the RoHS Directive, which stands for restriction of the use of certain hazardous substances [48], is to ensure that the electrical equipment, as well as the materials used in the construction of e-bikes, does not contain hazardous substances such as lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) [48].

4- Machinery directive

E-bikes within the EU market should comply with Directive 2006/42/EC; this directive sets certain essential health and safety requirements for e-bike design and construction requirements [48]. Notice that most of these requirements are indicated in EN 15194 [48]. In addition to Directive 2006/42/EC, the machinery directive has further obligations for manufacturers of e-bikes [48]. They must stick on their e-bike CE conformity marking. This marking must be visible on the e-bike [48]. However, The CE marking cannot be stuck on the e-bike if it does not comply with Directive 2006/42/EC, electromagnetic compatibility, and the RoHS Directive [48].

3.8. E-bike regulatory framework, usage and accidents patterns in Belgium

3.8.1. E-bike regulatory framework in Belgium

The Belgian traffic law “code de la route” defines an e-bike as a bike assisted by an electric motor with a maximum continuous rated power of 0.25 kW [32]. The power supply is gradually reduced and finally interrupted when the bicycle reaches a speed of 25 km/h or earlier if the rider stops pedalling [32]. However, according to Belgian traffic law, this definition does not change the classification of e-bike users as cyclists [32].

The regulatory framework shown in Appendix A, Table 30 provides a wide picture of the regulations governing the use of e-bikes in Belgium regarding technical specifications, use of infrastructure, and general rules of riding. In terms of technical specification, the EN 15194: 2017 Standard sets technical specifications for electric bicycles, specifying a rated continuous power of 250 watts [49]. Concerning the use of infrastructure, users of e-bikes are cyclists; therefore, the same rules applied to e-scooters, which are previously mentioned, are applied to e-bike users [32]. Expect the fact that users under the age of 10 years are allowed to use sidewalks [32].

In accordance with Belgian regulations for e-bike users, as outlined in Appendix A, Table 30 the following additional regulations are worth mentioning. While helmet use is not mandatory, it is highly recommended for all riders for safety reasons [50]. E-bike insurance to cover property damage is not mandatory [50]. Carrying children is allowed; however, e-bikes must be equipped with designated seating for child passengers, a dedicated child seat with two footrests is compulsory, and helmet use for children in such cases is highly recommended [32]. Also, the limitation for riding an e-bike under the influence of alcohol is 0.5 per mile (‰) [51]. Finally, there is no minimum age restriction for riding an e-bike [50].

3.8.2. E-bike usage in Belgium

In recent years, the usage of e-bikes in Belgium steadily grew. In 2018, 10% of the people in Belgium were using e-bikes; this percentage increased to 13% in 2019 and reached 16% in 2020 [52]. In 2022, almost 101,786 e-bikes have been sold to Belgian citizens, accounting for a 50% increase compared to 2021 [53].

To understand e-bike user characteristics in Belgium, we refer to an online survey conducted by the iVOX research office [54]. on behalf of the Federal Public Service Mobility and Transport with 2000 participants [54]. The survey was carried out between the second of December and the fifteenth of December 2019, aimed at the different modes of micromobility and their advantages and disadvantages [54]. The following modes were investigated: non-electric bicycles, e-bikes, speed pedelec, electric cargo bikes, and shared e-scooters [54]. The survey findings revealed that the usage of e-bikes was equally distributed between males and females [54]. In addition, users above 55 years old represent the highest usage.

3.8.3. E-bike accidents in Belgium

The Belgian road safety barometers provide data about the number of injuries from road accidents every three months [55]. In addition to the number of injuries, the road safety barometers provide the number of casualties, which refers to fatalities and injuries resulting from road accidents [55]. Such data are gathered by the federal police and reported each year [55].

Table 3 illustrates the number of accidents involving an e-bike from 2015 to 2022; notice that before 2015, the registration of e-bike accidents was not present in the federal police report [55], which explains the rapid increase of e-bike accidents in the last ten years due to the significant usage. Table 3 gives a detailed breakdown of e-bike severity levels resulting from accidents involving an e-bike [55]. Injury accident refers to slight injuries, serious injuries, and fatalities [55]. While fatality refers to a death occurring within 30 days after an accident [55].

Accident severity levels	2015	2016	2017	2018	2019	2020	2021	2022
Injury accidents	518	743	987	1442	1891	1989	2415	3378
Fatalities	15	13	20	21	25	29	34	37

Table 3: number of e-bike accidents in Belgium between 2015 to 2022.

Concerning the characteristics of users who are involved in e-bike accidents, Figure 10 shows the distribution of e-bike accidents across different age groups [55]. Around 50% of users who experienced an accident with an e-bike their age were over 50 years old [55]. This finding can be correlated with the result of the survey conducted by the iVOX research office, which found that the usage of e-bikes was predominant among people above 55 years [54]. The remaining e-bike accident distribution was as follows: users aged 0 to 10 years accounted for 1%, those aged 10 to 19 years constituted 9%, those aged 20 to 29 years constituted 14%, those aged 30 to 39 years represented 14%, and those aged 40 to 49 years constitute 13% [55].

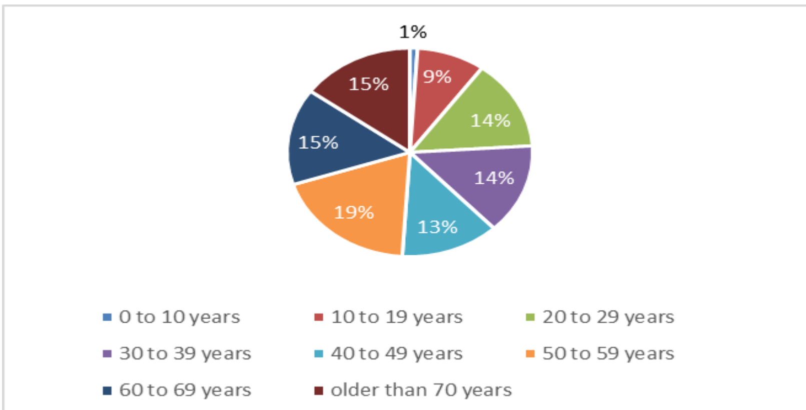


Figure 10: e-bike accidents by age group in Belgium in 2022.
Source: Statbel (Directorate General Statistics – Statistics Belgium).

3.9. E-bike regulatory framework, usage and accidents patterns in France

3.9.1. E-bike regulatory framework in France

The French traffic law "code de la route" defines an e-bike as a pedal-assisted bicycle equipped with an electric auxiliary motor with a maximum continuous rating power of 0.25 kilowatt [56]. The power is gradually reduced and finally interrupted when the vehicle reaches a speed of 25 km/h or earlier if the cyclist stops pedalling [56]. The e-bike is, therefore, considered as a conventional bicycle. The riders are then subjected to the same rules of cyclists. Appendix A, Table 31 provides comprehensive regulations concerning the use of e-bikes in France regarding technical specifications, the use of infrastructure, and general riding rules.

Concerning technical specifications, manufacturers must comply with EN 15194: 2017 Standard [57]. EN 15194: 2017 indicates technical specifications related to vehicle mechanical characteristics, battery specifications, and related technical tests [57].

When it comes to infrastructure usage, e-bike users are obligated to ride on cycle lanes whenever they are present [58]. However, in the absence of cycle lanes, they can ride on a road with a maximum speed limit of 30 km/h [59]. Although e-bike users can use road shoulders and pedestrian areas, riding on sidewalks is prohibited except for children under eight years old.

According to French traffic law, helmets are compulsory for users under 12 years old [60]. In accordance with French traffic law, the following regulations are also highlighted in Appendix A, Table 31: carrying children are allowed with a proper child set. However, the children must wear a properly fitted helmet [61]. It is worth mentioning that there is no age restriction for riding an e-bike, and e-bike insurance to cover property damage is not mandatory, but it is highly recommended [62].

Additional regulations outlined in Appendix A, Table 31, which significantly impact e-bike safety and they are necessary to prevent user disturbance. Cyclists, including e-bike users, are prohibited from wearing any device capable of emitting sound (headphones and earbuds) [61]. Also, the allowable limit for riding an e-bike under the influence of alcohol is 0.5 g/l [61].

3.9.2. E-bike usage in France

The Union Sport and Cycle Observatory shows interesting figures about the usage of e-bikes in France; in 2021, 660,000 e-bikes were sold, compared to 515,000 in 2020 [63]. In addition, the electric bike has seen a remarkable increase in the market share. In 2022, the electric bike accounted for 24% of the market volume and 59% in market value [63].

The personal mobility survey carried out in 2018 and 2019 is an essential source of information for measuring the mobility of French people at the national level and comparing it over time [64]. The objective of the survey is to describe people's mobility practices. The French personal mobility survey revealed that out of 16.6 million bikes used, 520,000 were electric bikes [64]. However, the personal mobility survey provides information about cyclists' socio-demographics characteristics as well as trip characteristics, considering all the different types of bicycles [64]. Therefore, we referred to a survey conducted by Cerema to better understand e-bike user characteristics [65].

Cerema, is a public institution supports the Ministry of Ecological Transition and Territorial Cohesion, and local authorities in developing, deploying, and evaluating public planning and transport policies [65]. The Cerema survey conducted between 2021 and 2023 provides detailed information about e-bike user characteristics [65]. The survey aimed to understand the characteristics of e-bike users. The number of observations utilized in the survey was 97,900 individuals, 626 of whom were e-bike users [65]. The findings from the survey show that e-bike users were, on average, older than 50 years old, and approximately half of the trips made using e-bikes were for commuting to work [65].

3.9.3. E-bike accidents in France

The National Interministerial Road Safety Observatory (Observatoire National Interministériel de la Sécurité Routière [ONISR]) provides road traffic accidents that occur on publicly accessible roads in France, including e-bike accidents. Figure 11 shows the number of e-bike accidents by region between 2019 to 2022.

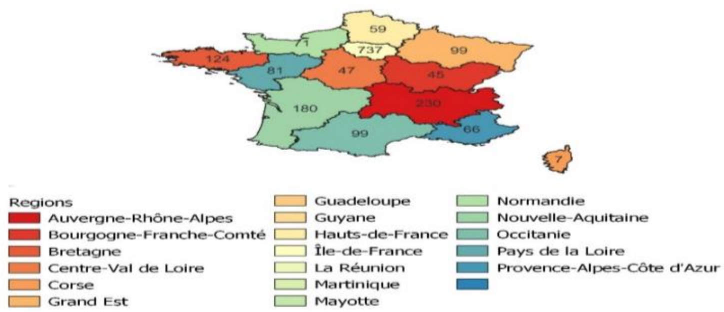


Figure 11: the distribution of e-bike accidents some French regions between 2019 to 2022- from QGIS 3.28.3 Firenze. Source : ONISR

As in the case of e-scooter accidents, the Île-de-France region reported the highest number of accidents, with 773, and the second highest number of e-bike accidents reported in the Auvergne-Rhône-Alpes region, with 230. Also, e-bike accidents were more likely to occur in urban areas. Figure 12 shows the percentage of e-bike accidents by land use patterns; 87% of the accidents were reported in urban areas; this can be correlated to the usage patterns where more e-bikes were used in the cities.

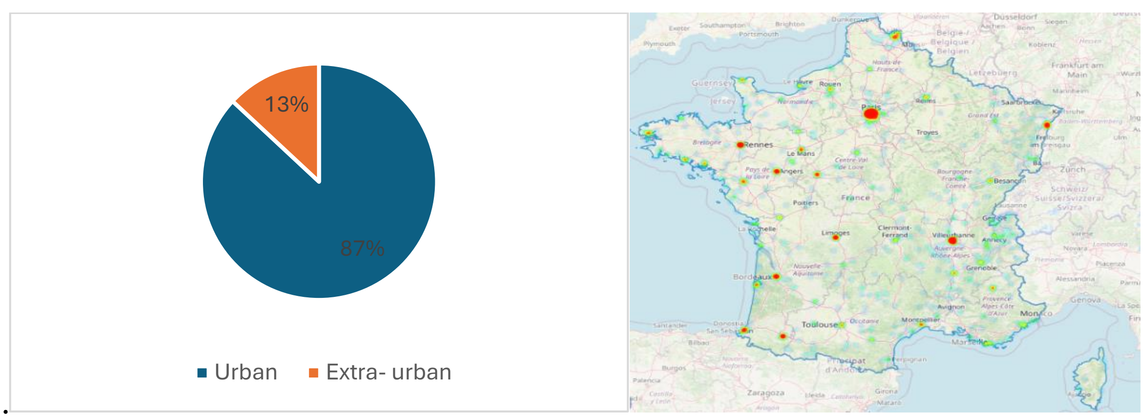


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Figure 12: percentage of e-bike accidents in France by land use patterns. Source: ONISR

The variation in the number of accidents observed in Figure 11 between the Île-de-France region and other regions is due to the concentration of accidents in Paris, which is also associated with the usage patterns. High usage of e-bikes was observed in Paris. Figure 13 illustrates the distribution of e-bike accidents in Île-de-France region while Figure 14 shows the concentration of accidents in Paris.

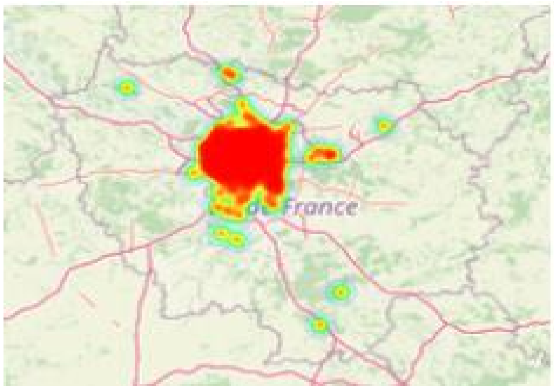

Figure 13: distribution of e-bike accidents in Île-de-France region between 2019 to 2020.
Source: ONISR

Figure 14: distribution of e-bike accidents in Paris between 2019 to 2022.
Source: ONISR

Regarding victims' sociodemographic characteristics, males experienced more accidents than females; this can be associated with usage patterns where males are cycling more than females. Regarding age, Figure 15 illustrates the percentage of e-bike accidents by age group in 2019 and 2020 [39], [41]. Users younger than 14 years, as well as users older than 85 years, experienced the lowest percentage. The percentage of e-bike accidents starts to increase significantly from the age of 24 years; this might be correlated to the findings from the Cerema survey, where approximately half of the trips made using e-bikes are for commuting to work. Interestingly, the similarities in the percentage of e-bike accidents experienced by users aged 55 years to 59 years in 2019 and 2020 are likely linked to the results of the Cerema survey. The findings from the Cerema survey show that e-bike users were, on average, older than 50 years.

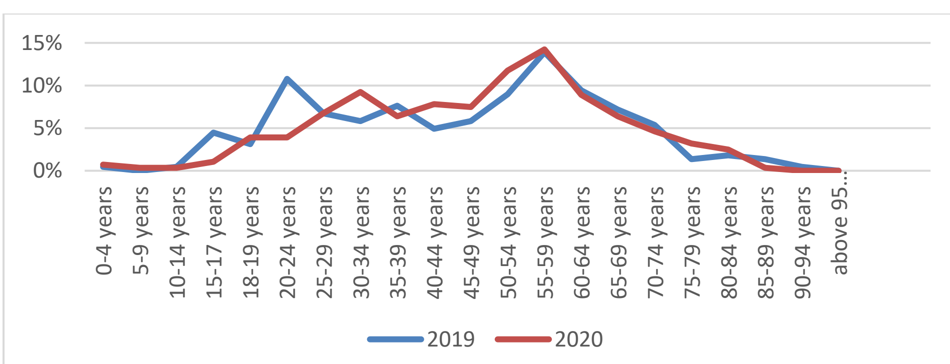

Figure 15: percentage of e-bike accidents in France by age group in 2019 and 2020.
Source: ONISR

3.10. E-bike regulatory framework, usage and accidents patterns in Germany

3.10.1. E-bike regulatory framework in Germany

The German Road Traffic Act (Straßenverkehrsgesetz [StVG]) defines e-bikes as vehicles propelled by muscle power and equipped with an auxiliary electric motor with a nominal continuous power of no more than 0.25 kilowatt [66]. The electric motor's assistance progressively decreases with increasing vehicle speed and is interrupted upon reaching a speed of 25 km/h or earlier when the driver stops pedalling [66]. The German Road Traffic Act considers e-bike users as conventional bicycle users.

The regulatory framework outlined in Appendix A, Table 32 governs the use of e-bikes in Germany regarding technical specifications, the use of infrastructure, and general riding rules. They are sourced from The German Road Traffic Act (Straßenverkehrsgesetz [StVG]), Road Traffic Regulations (Straßenverkehrs-Ordnung [StVO]), and The General German Automobile Club (Allgemeiner Deutscher Automobil-Club [ADAC]). The ADAC provides a wide range of mobility, travel, and safety services.

Regarding technical specifications, manufacturers must comply with EN 15194: 2017 Standard[1], which indicates technical specifications related to vehicle mechanical characteristics, battery specifications, and related technical tests.

Regarding infrastructure use, e-bike users are obliged to use the cycle paths whenever they are present [67]. However, in the absence of cycle paths, they are allowed to use roads with a speed limit of 30 km/h [68]. Additionally, the use of road shoulders is also allowed [68]. However, the use of sidewalks is strictly prohibited, and it is allowed only under specific conditions [67]. For instance, children under eight years are allowed to use the sidewalk [67]. If the child is accompanied by a suitable supervisor (above 16 years old), this supervisor may also use the sidewalk [67]. Pedestrian traffic must not be disturbed by e-bike users; if necessary, the speed must be adjusted to pedestrian traffic [67]. In addition, the use of motorways is strictly prohibited [68].

In accordance with the regulations presented in Appendix A, Table 32 the following regulations are worth mentioning since they influence e-bike user safety. In terms of safety equipment, there is no legal obligation for cyclists to wear helmets [69]; however, it is strongly recommended [69]. Cyclists may only listen to music at a volume that allows them to hear the traffic [68].

[1] https://www.bundestag.de/resource/blob/999522/5c851af7a125458ff868b13c2a8ee150/WD-5-042-24-pdf.pdf

Regarding carrying passenger, child bike seats are suitable for carrying children and must comply with the DIN EN 14344 standard [69]. Children between the ages of one and seven can travel in a child seat, and they are advised to wear a helmet for additional safety [69]. For alcohol drinking limit the legal limit for blood alcohol concentration is 1.6 ‰ (per mille) [68]. Finally, there is no restriction on the minimum age to use an e-bike [70].

3.10.2. E-bike usage in Germany

Germany is leading the electric bicycle market in Europe, with 2.1 million e-bikes sold in 2023 [46]. The Federal Ministry for Digital and Transport in Germany estimates that more than 1,600 electric bikes are sold every day [69]. Also, approximately one in thirty German citizens already own an e-bicycle. Given this rapid increase in e-bike purchases in Germany, it is worth understanding the user characteristics of such vehicles.

To understand the characteristics of e-bike users in Germany, we refer to a study based on the German household travel survey data. The survey was conducted from 2016 to 2017 and provides information on users and trip characteristics at the national level [71]. Regarding e-bike ownership, males own more e-bikes than females [72]. Also, the usage of e-bikes was more frequent among old individuals [72]. However, in 2021, figures showed that there were slight differences in e-bike usage among different age group [73].

3.10.3. E-bike accidents in Germany

The rapid increase in e-bikes in Germany, as illustrated in the previous section, raises concerns about their safety since they can travel at 25 km/h. Table 4 shows the number of e-bike accidents in Germany from 2019 to 2022. The e-bike accident data reported in the table shows a rapid increase throughout the year.

year	2019	2020	2021	2022
e-bike accidents	7,325	10,946	12,514	16,672

Table 4: number of e-bike accidents in Germany from 2019 to 2022.
Source: Federal Statistical Office of Germany.

We refer to previous studies on e-bikes and conventional bikes to understand the victim characteristics. The data utilized in the study were reported by the police in three federal states in Brandenburg, Hesse, and Saxony between 2012 and 2020 [74]. The study revealed that males experienced more accidents than females [74]; this result can be reasonable since males use e-bikes more frequently, as mentioned in the previous sections. In addition, the mean age for e-bike users involved in accidents between 2012 and 2016 was 61 years, then steadily decreased to reach 54 years in 2020 [74]. The decrease in e-bike accidents by mean age can be considered reasonable, as previously mentioned, since usage patterns in recent years have shifted from old individuals to slight equal distribution across different age groups.

4. Analysis and modelling of micro-mobility accidents in France and Belgium

In recent years, the usage of micro-mobility has increased significantly, and as a result, the number of accidents involving these vehicles has also grown [12]. From 2017 to 2022, U.S. emergency departments received around 360,000 victims of micro-mobility accidents injuries [1].

This Chapter aims to conduct a comprehensive analysis of micro-mobility accidents, with a particular focus on e-bikes and e-scooters. In addition, we develop a modelling framework to classify the severity levels of these accidents using a machine learning algorithm in the R programming language. Table 5 provides an overview of the countries targeted in the analysis and modelling, as well as the types of micro-mobility vehicles considered, based on the available data in each country. The analysis and the modelling aim to define the factors that contribute to specific severity levels of accidents, evaluate the effectiveness of the existing regulations, and propose regulatory adjustments to improve the safety of micro-mobility. In addition, it is essential to explore technological advancements that can lead to safer riding.

Country	e-bike	e-scooter
France	available	available
Belgium	available	not available

Table 5: micromobility and data availability for targeted countries.

Different modelling techniques can be used to study and analyse micro-mobility accidents data, as previously explained in Chapter 2. In our study the Random Forest algorithm is the machine learning algorithm selected for constructing the model. The selection of random forest is based on its capability to deliver high performance, particularly when dealing with imbalanced data distributions [11], [77], which is a common characteristic in micro- mobility accidents.

To summarize, this study aims to improve the safe usage of micromobility by analysing e-bike and e-scooter accidents with respect to users, infrastructure, and collision characteristics. In addition, the study seeks to examine how these factors influence the severity levels sustained by e-bike and e-scooter users. To achieve this, we built machine-learning models. The predicted classes by the models (dependent variables) were the severity levels of the accidents, while the independent variables were related to previously mentioned factors.

4.1. Datasets and related descriptive statistics

In this study, we used accident data reported by the police in France and Belgium. The French dataset represents traffic accidents reported by the police in 2022, which included 570 records for e-bike accidents and 1035 for e-scooter accidents. The Belgian dataset represents traffic accidents between 2014 and 2021, which includes 26,976 incidents where at least one e-bike was involved.

4.1.1. Data sources: the French and Belgian datasets

Regarding the French data, the dataset represents traffic accidents on publicly accessible roads recorded by the police in 2022. It has been gathered as part of the Corporal Accident Analysis Bulletin (Bulletin d'analyse d'accident corporel [BAAC]), which was administered by the French Road Safety Observatory (l'Observatoire national interministériel de la sécurité routière [ONISR]) as part of the National Road Traffic Accident. The data is structured into four files: users, places, vehicles, and characteristics. Appendix D, Table 33 shows the definitions of the attributes and their corresponding values regarding e-bike and e-scooter accidents data in France. The variable (Num_Acc), which represents the accident identification number in the four files, makes it possible to link the variables. After filtering and applying data preprocessing, we obtain 548 observations for e-bike. The same is made for e-scooter accidents, and we obtained 996 observations.

Regarding the Belgian data, the dataset utilized in this study to analyse and model e-bike accidents was obtained from the official statistics in Belgium (Statbel) after formal communication with Statbel. Notice that in 2014, the Federal Police began sending data on electric bikes to the (Statbel). Thus, the data represent e-bike accidents from 2014 to 2021, where at least one electric bike was involved in the accidents with 21,087 observations after applying data preprocessing. Appendix D, Table 34 shows the attributes their corresponding values presented in the dataset. However, Belgium lacks such disaggregated data concerning e-scooters, as mentioned earlier in this Chapter; therefore, in the case of Belgium, we only consider e-bike accidents in our analysis and modelling.

4.1.2. Definition of the endogenous variable: accidents severity levels in France and Belgium

Many countries rely on the frequency of road traffic fatalities when monitoring road safety performance [83]. However, road accidents also lead to many severe and minor injuries [83]. According to the European Commission, for each individual who loses their life, five others experience serious injuries [84]. The source of data can define different severity levels. However, the primary accident data sources typically include police records and hospital trauma data registries [83]. Police accident data, for the most part, serve as the cornerstone of information on road traffic accidents. They furnish official statistics at both national and European levels with the necessary traffic accident data [83]. Despite the absence of a standard international definition for traffic injury, the vast majority of European countries are relying on the definitions developed by ITF/ Eurostat/ UNECE, which categorize severity levels resulting from road accidents into three categories: slight injury, serious injury, and fatality [85]. Based on these definitions, a fatal accident is when the victim involved dies within 30 days after the accident due to sustained injuries—a person classified as seriously injured who required hospitalization for a period that exceeds 24 hours [85]. The slight injury category excludes those who have suffered fatalities or serious injuries [85]. Besides the previous definitions, other countries utilize alternative definitions for serious injury linked to the ability to work and the period of recovery [86]. The dataset utilized in the analysis for this study was gathered by the police in France and Belgium, thus adopting the police classification for severity levels of accident injuries. These severity levels therefore encompass no injury, slight injury, serious injury, and fatality, as previously discussed.

In some countries, Hospital trauma data registries adopted the Abbreviated Injury Scale (AIS), which is an ordinal scale of 1 to 6 (1 indicating a minor injury and 6 being maximal non-treatable injury) [83]. AIS equal to or higher than three on the AIS is classified as clinically seriously injured (MAIS3+) [83].

The degree of severity levels correlates with the accident mechanism, the type of vehicle involved, and the road users engaged [12]. E-scooter accidents lead to injuries that affect the head and the face, with a significant proportion of maxillofacial injuries notably concentrated in the lower portion of the face [87], [88], [89], [90]. In terms of e-bike accidents, cyclists can sustain maxillofacial injuries even with the use of a helmet [91]. In addition to injuries to the head and face, e-scooter accidents frequently result in injuries to the upper and lower extremities [16], [93]. Lower extremity damage and fractures, especially those affecting the wrist and lower arm, are frequent among e-scooter users [87], [94]. It is crucial to emphasize that most injury categories are not exclusive, and many patients have more than one type or position of damage.

4.1.3. In-depth investigation: description of e-scooter and bicycle riders' injuries from hospitals records in the Rhône Department in 2019

Table 6 shows the injuries and injury type position for around 3000 patients in the hospital at the Rhône Department of France in 2019 [95]. Head, face, and neck injuries experienced by e-scooter users are higher than the same injuries experienced by cyclists; this can be linked to the less usage of helmets among e-scooter users, injuries to the lower extremities are more common among e-scooter riders compared to cyclists, potentially indicating injuries sustained as e-scooter riders dismounted their vehicles just before or during the loss of control [95].

	E-scooter	E-bike
Number of victims	825	1945
Use of helmet	6.1%	30.7%
Severity level (>AIS3)	1.9%	1%
Head injury	24.2%	19.9%
Face injury	30.6%	20.5%
Neck injury	3.3%	2.5%
Thorax injury	7.3%	9%
Spine injury	6.7%	7.9%
Upper extremities injury	48.9%	57.6%
Abdomen pelvis injury	3.4%	3.2%
lower extremities injury	41.8%	38.8%
Admitted to intensive care	2.1%	1.7%

Table 6: a comparison of injuries sustained by e-scooter and e-bike riders presents at hospital Rhone department of France in 2019.
Source: G. Yannis, V. Petraki, R. Associate, and P. Crist,2024.

4.1.4. Factors influencing micro-mobility accidents severity: how are they captured in the two datasets

The analysis and modelling aim to investigate the influence of three main factors: rider, infrastructure, and collision characteristics on micro-mobility accidents. These factors are commonly indicated in existing literature when analysing micromobility accidents [11], [14], [96]. Rider characteristics can provide valuable insights for urban planners and healthcare systems by identifying the risks related to users and addressing the proper policies that can cope with these risks [12]. Infrastructure characteristics are also crucial in improving safety by designing appropriate geometry [11], and applying interventions for existing infrastructure. Also, understanding collision characteristics can assist in identifying technology improvements for micro-mobility. The datasets used in the analysis originate from two countries (France and Belgium). Therefore, the variables within these three factors can differ. Appendix D, Table 35 illustrates a comparison of these datasets.

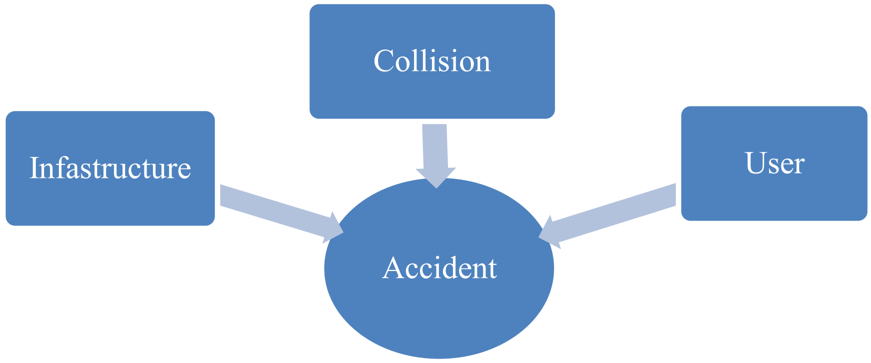

Figure 16: variables influencing micromobility accidents.

In summary, both countries provide information regarding user characteristics related to gender and age. However, the French dataset indicates the user's birth year, while the Belgian dataset offers the user's age in terms of age groups. Moreover, the French dataset provides valuable insights into user characteristics, including trip purpose, the day/time of the accidents, and the use of safety equipment. In contrast, data from Belgium lack such detailed user-specific information.

Both country's datasets lack essential information related to user characteristics that have a direct influence on accident occurrence, such as riding under the influence of alcohol. Studies have shown that accidents involving users under the influence of alcohol are more likely to experience injuries [87], [97], [98].

Two specific variables that are notably absent from the datasets are the effect of dual riding and the use of mobile phones while riding a micro-mobility vehicle. A Berlin-based survey, for instance, revealed that 42% of the people had experienced dual riding [99]; the effect of dual riding on an e-scooter can be critical, as it can increase the difficulties when the rider needs to perform foot braking in some e-scooter models, thereby increasing the challenges of performing the manoeuvre [99].

In terms of infrastructure, while both datasets provide information about infrastructure characteristics regarding the intersection types and circulation regime, the French dataset includes more detailed information on the road characteristics. Such as road type, number of lanes, allowable speed on the road, and further information on surface conditions such as wetness, icy conditions, or oil presence. In contrast, the Belgian data set provides aggregate information regarding the infrastructure characteristics. For instance, the attribute values for the infrastructure characteristics contain some types of intersections, the type of infrastructure, and the situations of the road in terms of ongoing constructions on the roads. Also, both datasets lack information related to surface quality; a study revealed that surface quality identified as an essential factor that has an impact on e-scooter collision; poor surface quality, such as defects, cracks, and discontinuities, is responsible for about 30% to 40% of e-scooter accidents [100].

Concerning collision characteristics, both datasets provide information about the collision types (rear, frontal, side, etc.) and the object involved, whether it is a moving object like a vehicle, pedestrians, or fixed obstacles. However, Belgian dataset provides aggregate information regarding collision characteristics. As for severity levels, both datasets gathered by the police indicate four levels of severity: no injury, slight injury, serious injury, and fatality, as discussed in the previous section.

4.1.5. Descriptive statistical analyses from the two datasets

We conducted statistical descriptive analysis through R programming language to understand the distribution of e-bike accidents in France, e-bike accidents in Belgium, and e-scooter accidents in France separately. The distribution of the accidents was conducted through bar charts with respect to the previously mentioned risk factors.

4.1.5.1. Descriptive statistics of e-bike accidents in France

4.1.5.1.1. User and trip characteristics

The attributes of user and trip characteristics in the French dataset include gender, age, trip purpose, time, and safety equipment usage. Figure 17 clearly illustrates the gender difference in e-bike accidents, with males experiencing 65% of incidents compared to females at 35%. This difference is mainly attributed to the different usage patterns, as men account for most bicycle trips in the country [101]. To understand the e-bike accidents across different ages, which can be beneficial in building the model, age segmentation is made; however, the dataset gives information about the year of birth of the users involved in the accidents. Figure 18 shows the percentage of e-bike accidents by age group. Riders below 10 years old experienced the lowest percentage of accidents, and users between the ages of 11 and 20 years old accounted for nearly 10%. In addition, the percentage of accidents appeared to be relatively stable across other age groups, with a slightly higher percentage for users above 60 years.

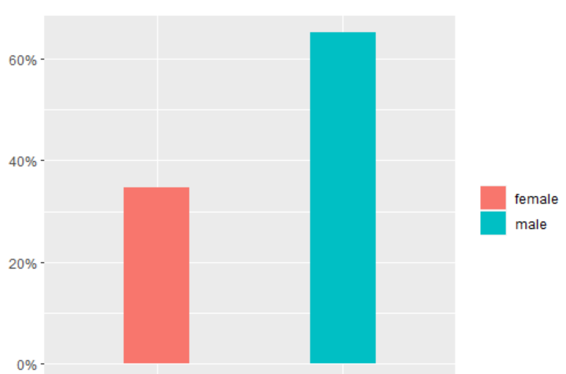

Figure 17: percentage of e-bike accidents by gender.

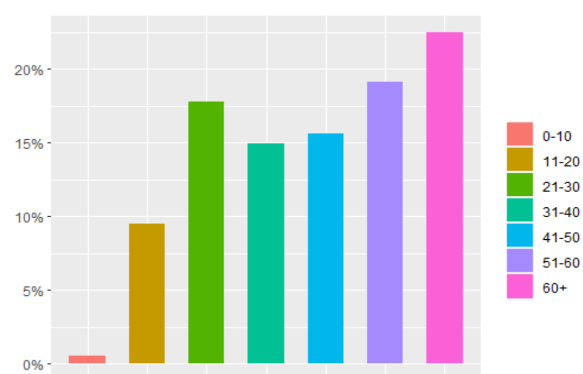

Figure 18: percentage of e-bike accidents by age group.

Figure 19 shows the percentage of e-bike accidents by trip purpose. Leisure trips constitute 37% of e-bike accidents, while home-school and purchase trips each account for only 2% each. However, around 28 % of accidents lacked sufficient information, approximately 15% identified as not specified, and 13% categorized as "other." Nearly 31 % of the accidents occur during home–work trips, representing the second highest percentage of accidents. Looking at how e-bike accidents vary throughout the day and week, Figure 20 reveals interesting patterns. Accidents are most frequent around 8:00 in the morning, then steadily decrease until 3:00 in the afternoon. After 3:00 pm, the accidents fluctuate until 7:00 in the evening, and then they decrease significantly.

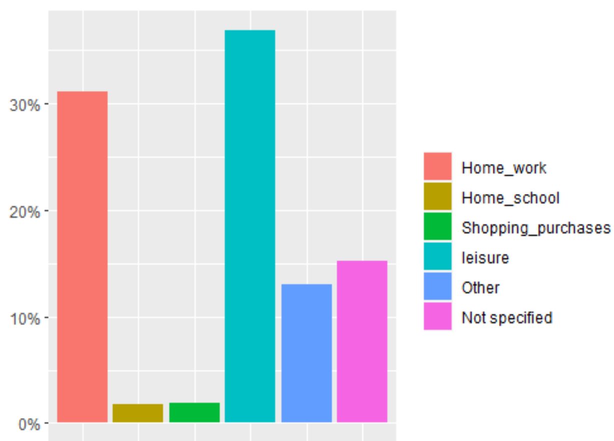

Figure 19: percentage of e-bike accidents by trip purpose

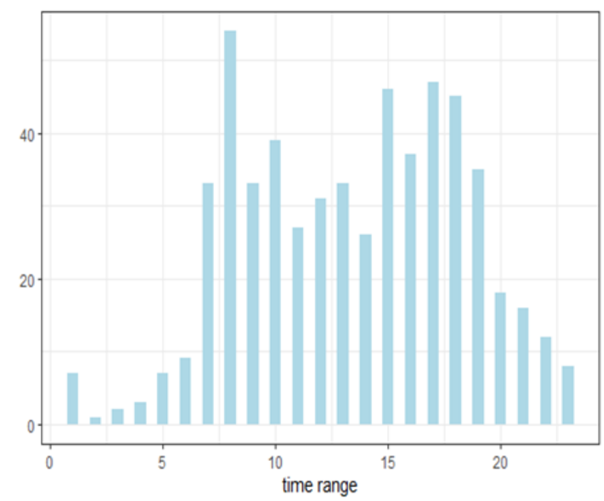

Figure 20: Time of day distribution of e-bike accidents.

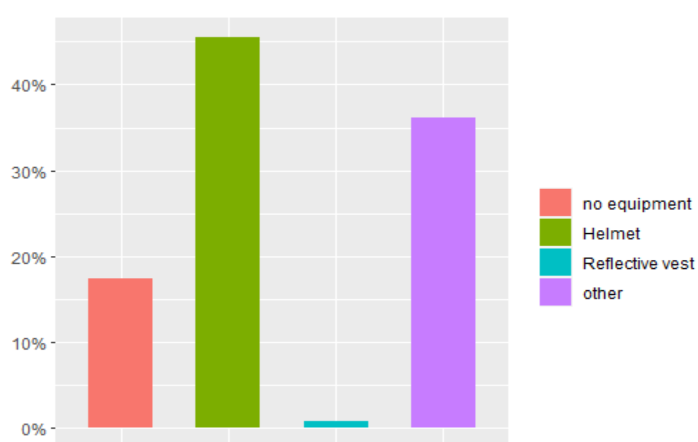

Figure 21: Percentage of the use of safety equipment.

Figure 21 explores the usage of safety equipment during e-bike accidents, merely focusing on the absence of safety equipment, the use of helmets, and reflective vests. Thus, other types of safety equipment are grouped into "others." The use of helmets was observed in 45% of the accidents, while the non-use of any kind of safety equipment was around 17%. However, wearing a reflective vest had a percentage of less than 2%.

4.1.5.1.2. Infrastructure characteristics

The French dataset encompasses several attributes when it comes to evaluating infrastructure characteristics. These include the land use pattern, distinguishing between urban and non-urban areas, the presence of light in the surrounding environment, the road speed limit, and the accident location in terms of roadway positioning, such as on lanes, shoulders, etc., and the number of lanes.

Figure 22 differentiates between accidents in urban and non-urban areas; most accidents occurred in urban areas, accounting for around 85%, whereas 15% occurred in non-urban areas; this can be linked to the usage pattern, where e-bikes are mostly used in cities. Regarding accident locations on the roadway, the analysis reveals that the two most prevalent positions where e-bike accidents occurred were on road lanes, approximately 73%, and on cycle lanes, comprising 20%. Other positions, such as on shoulders, special routes, and other areas, were less frequent, each accounting for less than 2% of accident occurrences (see Figure 23).

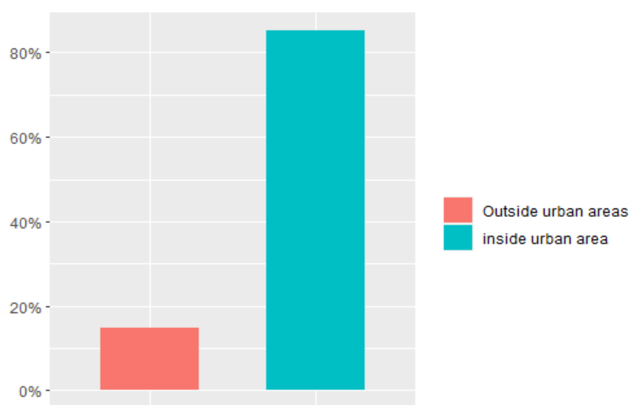

Figure 22: percentage of e-bike accidents by land use patterns.

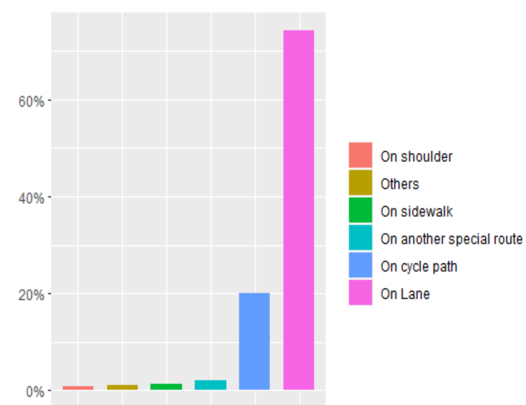

Figure 23: percentage of e-bike accidents by location on the road.

Regarding road speed limits, 88% of e-bike accidents occurred on roads with a speed limit lower than 50 km/h, as shown in Figure 24, while 12% took place on roads with a speed limit higher than 50 km/h. In terms of lighting conditions, 76% of accidents occurred during daylight, 17% at night when the public lights were on, 2% when the public lights were not present, and 5% during dusk (see Figure 25).

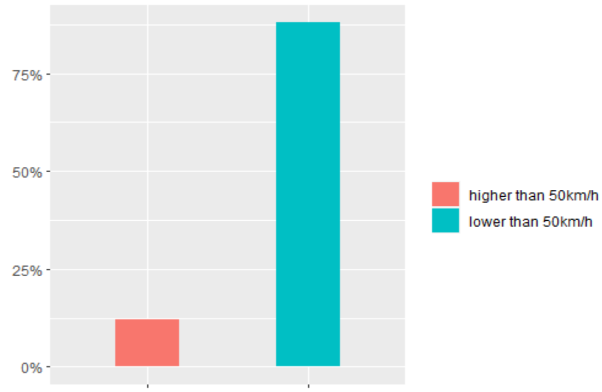

Figure 24: percentage of e-bike accidents by the max allowable speed on the road.

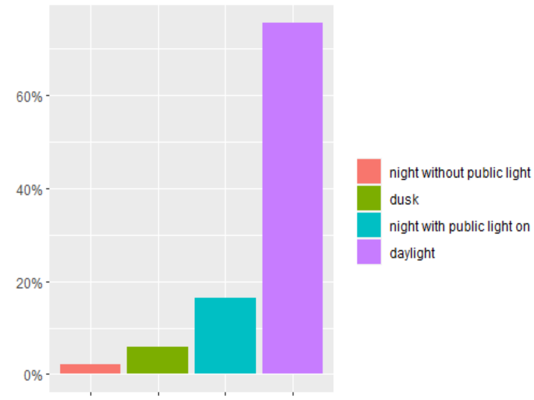

Figure 25: percentage of e-bike accidents by road lighting conditions.

The analysis of e-bike accidents by road characteristics revealed the following, as seen in Figure 26, Figure 27, Figure 28, and Figure 29. First, examining the curvature type, we see that a high percentage of accidents occurred on straight roads, 80%. Second, most accidents occurred outside the intersection 45%; third, the number of lanes is grouped, given the potential impact they can have on the rider's manoeuvres. In this analysis, the number of lanes is grouped into one lane, two lanes, and more than two lanes; accidents on two lanes were prevalent, accounting for 60%. Finally, most accidents occurred on municipal roads, accounting for around 65%.

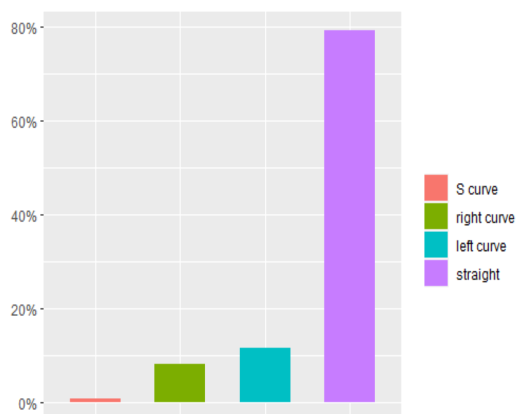

Figure 26: percentage of e-bike accidents by curvature type.

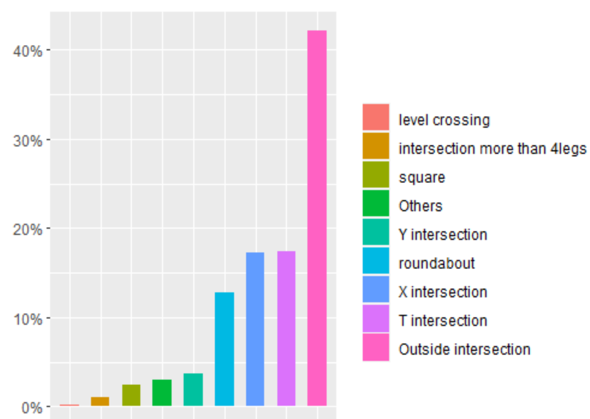

Figure 27: percentage of e-bike accidents by intersection type.

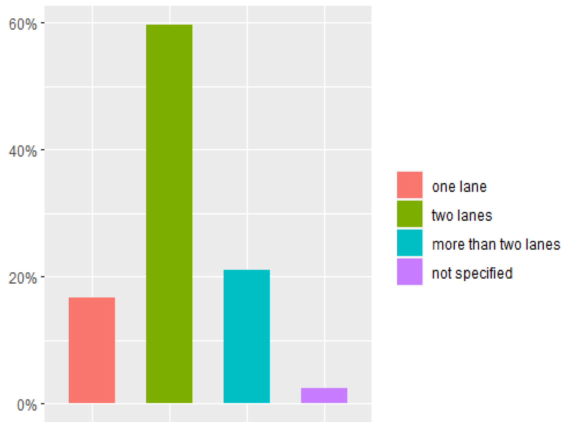

Figure 28: percentage of e-bike accidents by lanes number.

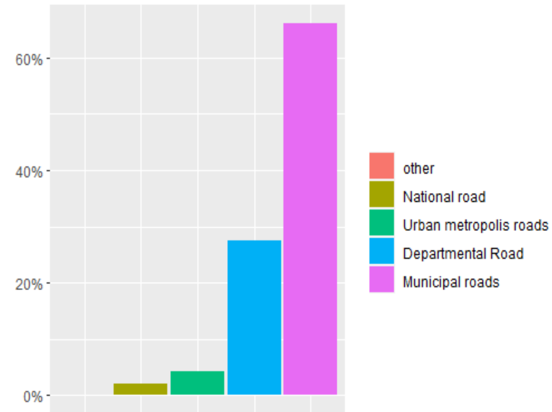

Figure 29: percentage of e-bike accidents by road type.

4.1.5.1.3. Collision characteristics

The French dataset provides detailed information on collision characteristics and the object involved, whether moving or stationary. As shown in Figure 30, side collision was the most frequent type, 60 %, followed by rear, around 12%; frontal and accidents without collision were approximately 11% each, and series and multiple collisions were rare, accounting for less than 1%. Regarding moving objects, 78% of accidents were involved in accidents with motor vehicles, while 20% of accidents lack information and have been categorized as none. Collisions with pedestrians, wildlife, pets, or other objects are uncommon, less than 1% (see Figure 31).

When examining e-bike accidents with fixed objects, as shown in Figure 32 there is a substantial lack of data; for instance, accidents with fixed objects such as walls, bridge piers, urban furniture, post singe, objects on the sidewalk or shoulder, parked vehicles, and existing roads without obstacles combined were accounted for 10% of accidents, 90% of accidents identified as none. This rises the concern about the quality of data collected when identifying the nature of the fixed object involved on the accidents.

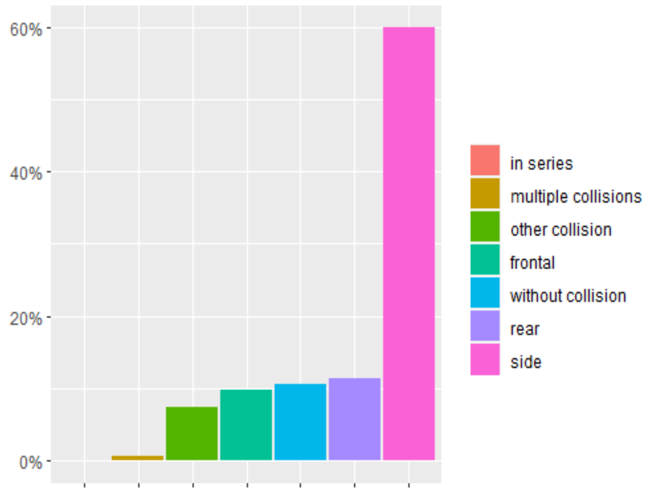

Figure 30: percentage of e-bike accidents by collision type.

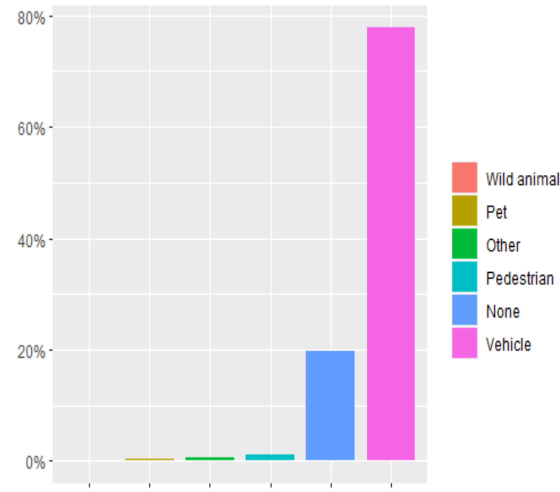

Figure 31: percentage of e-bike accidents by moving obstacles.

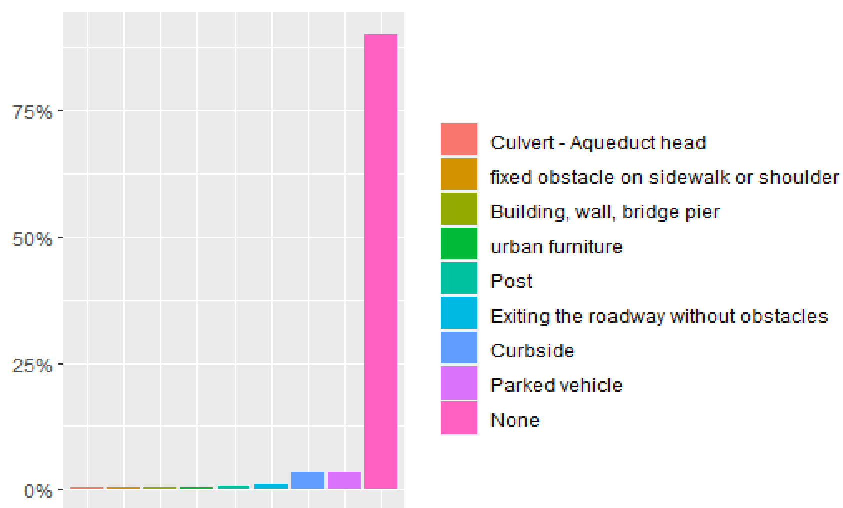

Figure 32: percentage of e-bike accidents by fixed obstacles.

4.1.5.2. Descriptive statistics of e-bike accidents in Belgium

4.1.5.2.1. User sociodemographic characteristics

The sociodemographic characteristics that are present in the Belgian dataset contain only two attributes: gender and age. Figure 33 illustrates the percentage of e-bike accidents in Belgium by gender. We can see no gender variability in the percentage of accidents experienced by males and females. This finding can be correlated to the usage patterns as illustrated in Chapter 3 by the findings from the iVOX research office survey, where the usage of e-bikes was equally distributed between males and females.

Figure 34 shows the distribution of e-bike accidents by age group. Users over 50 years have experienced the highest percentage of accidents, accounting for approximately 55%, also linked to the usage pattern. The iVOX research office survey found that individuals above 55 years old were using e-bikes frequently. The remaining percentage of accidents by age group was distributed as follows: less than 2% of the accidents were experienced by children with ages lower than 10 years, users between 10 to 19 years experienced 7% of the accidents, 13% for users between 20 to 29 years, 11% for users between 30 to 39 years, and users between 40 to 49 years experienced 13%.

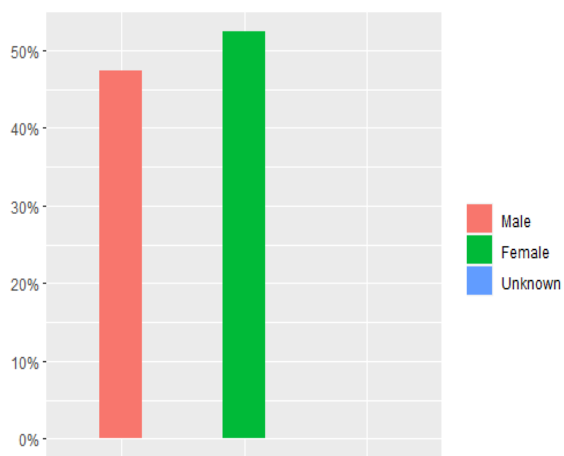

Figure 33: percentage of e-bike accidents by gender.

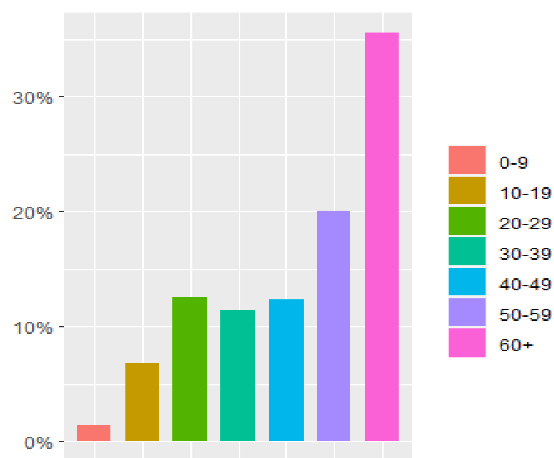

Figure 34: percentage of e-bike accidents by age groups.

4.1.5.2.2. Infrastructure characteristics

Regarding the infrastructure characteristics, the Belgian data lacks detailed information concerning the infrastructure characteristics compared to French data, as previously mentioned. Figure 35 shows the percentage of e-bike accidents in Belgium due to several factors that affect the roadway, such as the type of infrastructure and the roadway situation in terms of construction work that might affect the safety of the road. The combined category, which aggregates the construction work that affects the roadway, had negligible effects on the percentage of e-bike accidents. Similarly, accidents occurred in the tunnels and railway level crossings. In addition, e-bike accidents that occurred in bridges or viaducts represent a small fraction, nearly 3%. Slightly over 5% of the accidents occurred in roundabouts; this might be associated with roundabouts, as they enable drivers to react to potential conflicts more effectively due to lower speeds [102]. Moreover, around 20% of e-bike accidents were labelled as unknown, and more than 60% were labelled as none of the above; this suggests the need to improve the data collection.

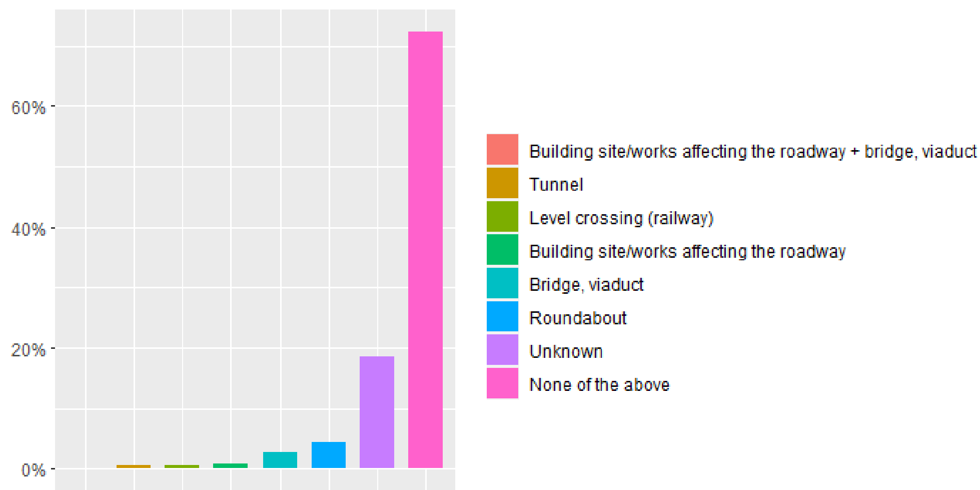

Figure 35: percentage of e-bike accidents by infrastructure characteristics.

Concerning the percentage of e-bike accidents by the position of the e-bike users on the road, it is important to define the different types of cycle paths according to Belgium traffic regulations. Such cycle paths are designed and marked to ensure safe riding for cyclists, including e-bike users, and they are defined as follows [103].

- On the road cycle path (marked on the ground)

The two parallel discontinuous white lines marked on the roadway, as shown in (Appendix B), indicate the presence of such a cycle path, and it is designated merely for cyclists [103]. Other vehicles are prohibited from using this on-road cycle path [103]. However, some other users of two-wheel vehicles might use it but with specific consideration [103].

- Off-Road Cycle Path

This type of cycle path is indicated by signs D7 or D9 (Appendix B) [103]. It is common for the road manager to make such cycle paths with another covering or color to make them more distinguishable [103].

- Suggested Cycle Lane

The suggested cycle lane is not a cycle path and has no legal status in the highway code [103]. It indicates the optimal position of the cyclist on the road and materializes by red ground markings, sometimes with the pictogram of a cycle [103].

Figure 36 shows the percentage of e-bike accidents according to the users' positions. Around 5% of the accidents occurred when riding or leaving the suggested cycle lane. This lower percentage indicates that users are relatively safe using such cycle lanes, likely due to reduced traffic conflict in such spaces. Approximately 11% of users experienced accidents when they were riding on the carriageway or when they were getting off the carriageway. This percentage was around twice the percentage when riders were using the suggested cycle path, indicating the possibility of conflicts with other vehicles. In addition, about 17% of the accidents occurred in cycle lanes separated from the carriageway. Such paths may experience conflicts at intersections and driveways.

The highest percentage of accidents (36%) occurred when riding on a road cycle path (marked on the ground), as seen in (Appendix B); this cycle path might lead to significant interaction with other vehicular traffic. Finally, 32% categorized as none of the previously mentioned positions indicate a lack of beneficial information within this category and highlighted the need for improvement in data collection.

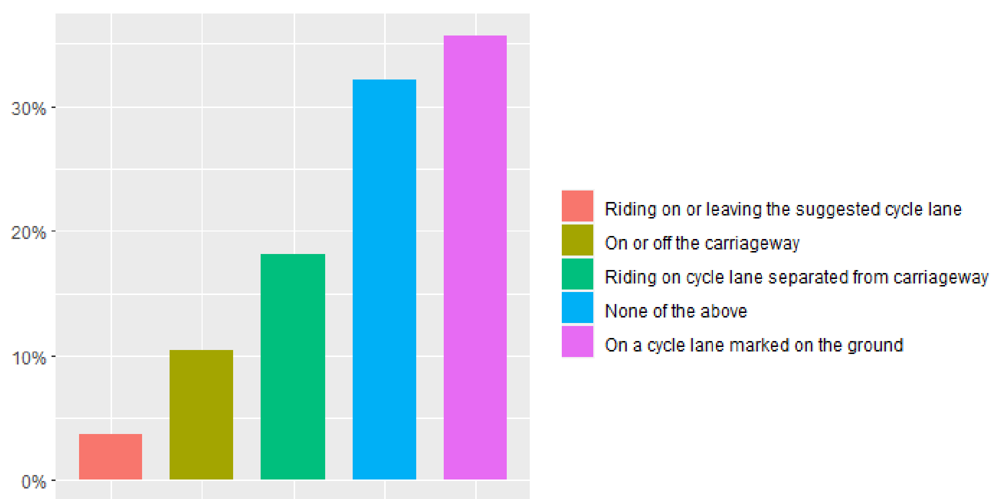

Figure 36: percentage of e-bike accidents according to the rider positions.

4.1.5.2.3. Collision characteristics

Figure 37 shows the percentage of e-bike accidents regarding collision characteristics; the highest collision type experienced in e-bike accidents in Belgium was side collisions, which occur from (front, back, and side), accounting for 51% of the accidents, followed by side against-side collisions, representing 12% of the accidents. In addition, head-on collisions accounted for 11%, while accidents not involving objects, including falls, represent 10%. Rear collisions accounted for 6%. Approximately 4% involved with pedestrians. Accidents against obstacles in or off the carriageway represent less than 3% each, and the chain collisions were seldom less than 1%.

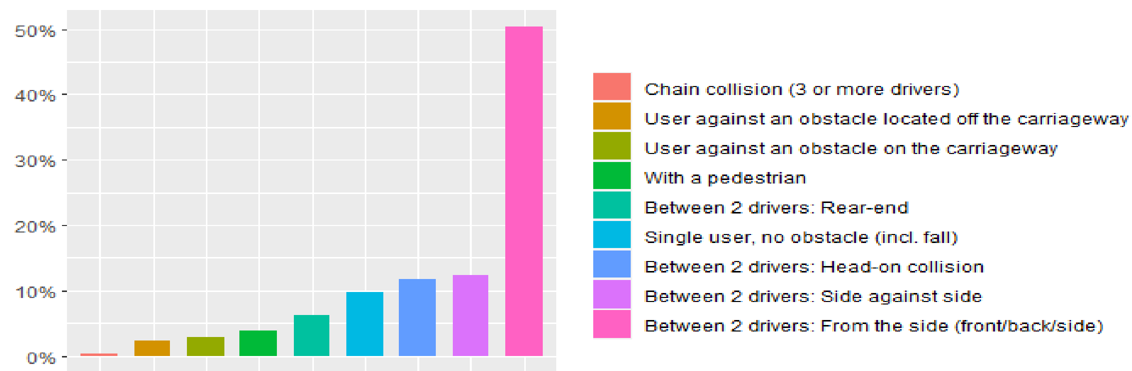

Figure 37: percentage of e-bike accidents by collision characteristics.

Figure 38 shows the percentage of e-bike accidents in Belgium concerning the vehicles involved in accidents. Passenger cars were involved in a significant number of accidents, accounting for 60%, indicating potential conflicts between e-bike users and passenger cars due to shared road areas. The second vehicle that conflicts with an e-bike is a normal bicycle, also due to shared areas on the roads and cycle paths, represented by approximately 12%. While van accidents against e-bikes account for 8%, pedestrians represent 4%. The remaining vehicles involved in e-bike accidents were uncommon.

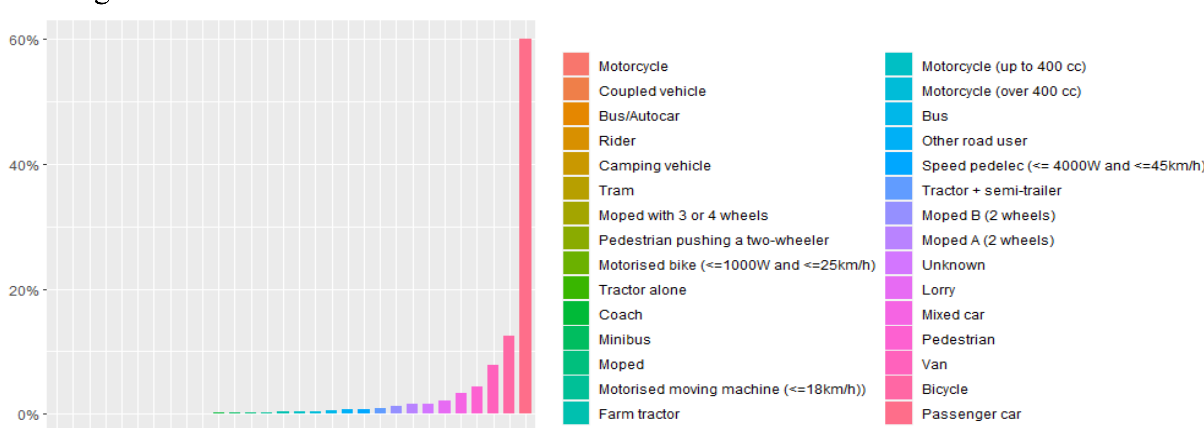

Figure 38: percentage of e-bike accidents by vehicle involved.

4.1.5.3. Descriptive statistics of E-scooter accidents in France

4.1.5.3.1. User and trip characteristics

As previously mentioned, the official e-scooter accidents data are combined with other types of personal motorized transport vehicles (Engin de déplacement personnel motorisé [EDPm]). Also, it is worth mentioning that the exact source of e-bike accident data provides data concerning (EDPm) as previously mentioned in the data section. The attributes of user and trip characteristics in the French dataset include gender, age, time, and safety equipment usage. Figure 39 illustrates the gender difference in accidents, with males experiencing 70% of incidents compared to females at 30%; this might be correlated to usage patterns since males are using more e-scooters than females according to results of the face-to-face survey conducted in Paris, which was previously mentioned in Chapter 3, e-scooter users were predominantly young males, accounting for 70%.

To understand the EDPm accidents trend across different ages, which can be beneficial in building the model, age segmentation is made; however, the dataset gives information about the year of birth of the users involved in the accidents. Figure 40 shows the percentage of EDPm accidents by age group. Riders below 16 years old, the legal age for riding an e-scooter in France, experienced around 10%. Users between 15 and 30 years accounted for the majority of accidents, which is a reasonable percentage given the result from the Paris survey that 85% of e-scooter users were under 35 years old. Users between the ages of 31 and 45 years old experienced 25% of the accidents, and nearly 12% of accidents accounted for those aged between 46 and 60 years old. Finally, users above 60 years old experienced fewer accidents due to the rare usage of e-scooters at such an age.

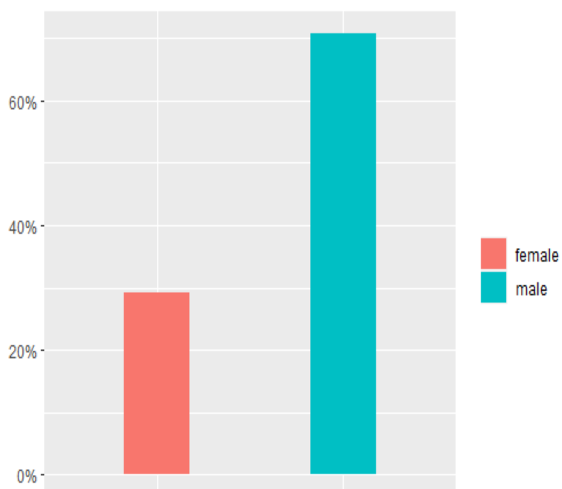

Figure 39: percentage of EDPm accidents by gender.

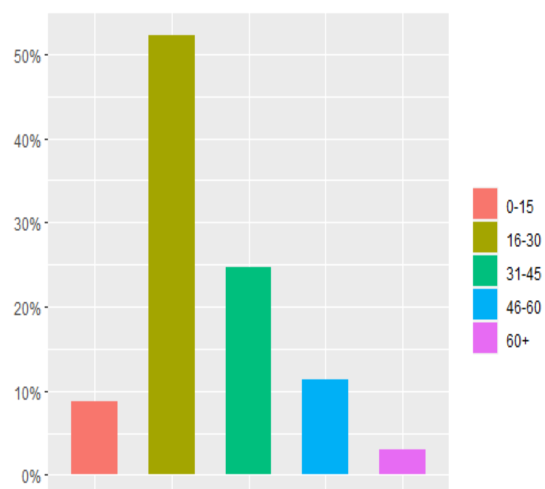

Figure 40: percentage of EDPm by age groups.

Figure 41 shows the percentage of EDPm accidents by trip purpose. Leisure trips constitute 26% of EDPm accidents, home-school accounted for 5%, and purchase trips only 2%. However, around 43 % of accidents lacked sufficient information, approximately 30% were identified as not specified, and 13% were categorized as "other." Nearly 25% of the accidents occurred during home–work trips, representing the second highest percentage. Looking at how EDPm accidents vary throughout the day, Figure 42 reveals the following patterns. Accidents occurred more frequently in the morning from 7:00 to 9:00 a.m. and in the evening from 4:00 to 7:00 p.m.

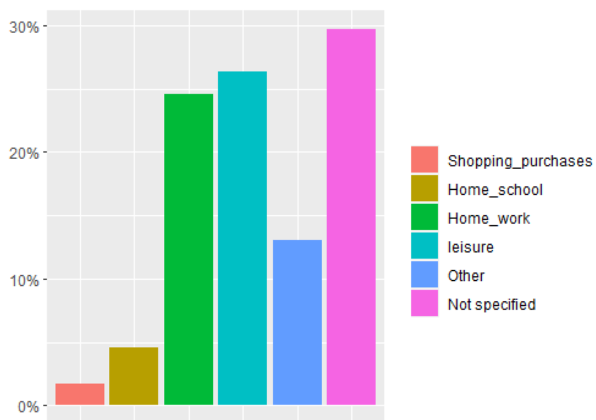

Figure 41: percentage of EDPm accidents by trip purpose.

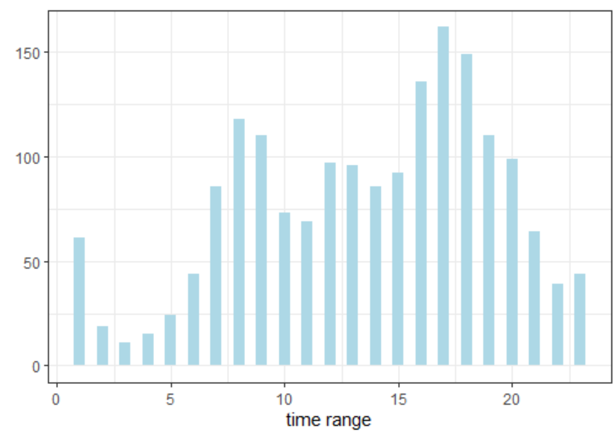

Figure 42: Time of day distribution of EDPm accidents.

Figure 43 explores the usage of safety equipment during EDPm accidents, merely focusing on the absence of safety equipment, use of helmets, and reflective vests. Thus, other types of safety equipment are grouped into "others." The use of helmets was observed in 24% of the accidents, which is lower compared to e-bikes. At the same time, the non-use of any safety equipment was around 18%, Less than 1% of users wore a reflective vest, 58% were categorized as other, and less than 1% were not specified.

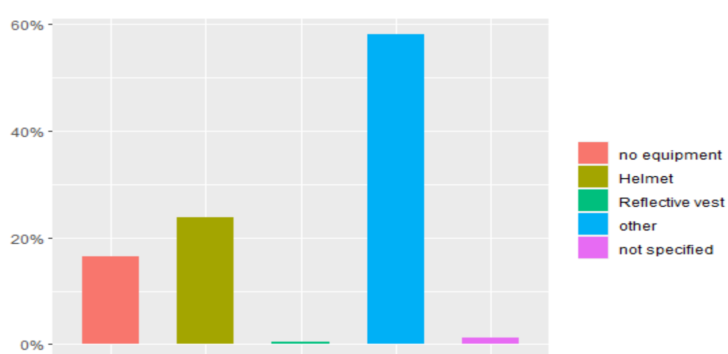

Figure 43: percentage of the use of safety equipment.

4.1.5.3.2. Infrastructure characteristics

As previously mentioned, the French dataset encompasses several attributes when evaluating infrastructure characteristics. These include the land use pattern, distinguishing between urban and non-urban areas, the presence of light in the surrounding environment, the road speed limit, and the accident location in terms of roadway positioning, such as on lanes, shoulders, etc., and the number of lanes.

Figure 44 differentiates between accidents in urban and non-urban areas; most accidents occurred in urban areas, accounting for around 98%, whereas 2% occurred in non-urban areas. This is merely due to the availability of shared e-scooter services in the cities, which represents a high amount of e-scooter usage. Regarding accident locations on the roadway, the analysis reveals that the most prevalent positions where EDPm accidents are more likely to occur were on road lanes, approximately 78%, warning us of the increasing risks that EDPm users might face with vehicular traffic. While accidents on cycle lanes accounted for 15%, other positions, such as on shoulders, special routes, and other areas, were less frequent, each accounting for less than 2% of accident occurrences (see Figure 45).

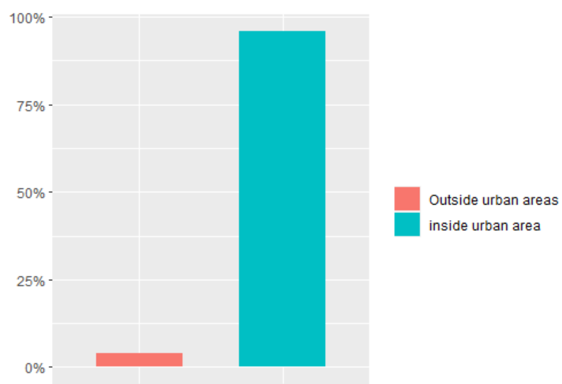

Figure 44: percentage of EDPm by land use patterns.

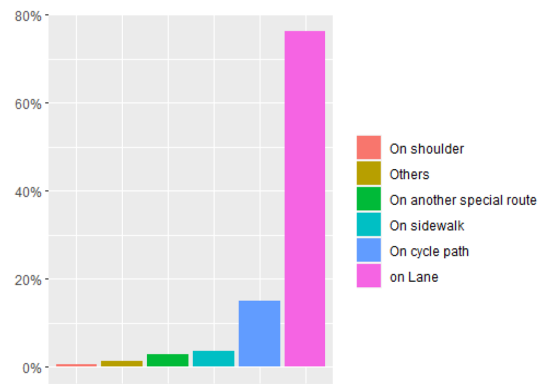

Figure 45: percentage of EDPm accidents by location.

Regarding road speed limits, according to French regulations, riding an e-scooter is allowed on roads with a speed limit of less than 50 km/h. Also, on roads with a speed limit of less than 80 km/, but on such roads, users are obligated to wear helmets and reflective vests, as previously mentioned in Chapter 3. Figure 46 shows that 98% of accidents occurred on roads with a speed limit of less than 50 km/h. Regarding lighting conditions, 69% of accidents occurred during daylight, 22% at night with public lights on, 2% when the public lights were absent, less than 1% of accidents occurred when the public light was off, and nearly 6% during dusk (see Figure 47).

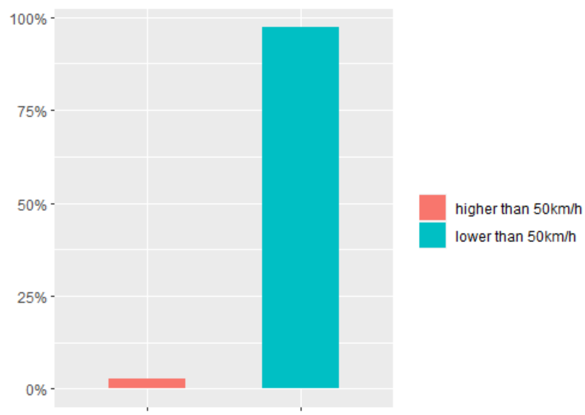

Figure 46: percentage of EDPm accidents by the max allowable speed on the road.

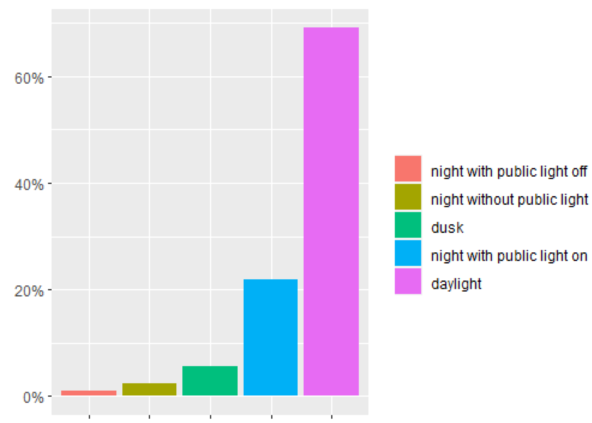

Figure 47: percentage of EDPm accidents by the lighting condition of the roads.

The analysis of EDPm accidents by road characteristics revealed the following, as seen in Figure 48, Figure 49, Figure 50, and Figure 51. First, examining the curvature type, we see that a high percentage of accidents occurred on straight roads, 88 %. Second, most accidents occurred outside the intersection 42%; third, the number of lanes is grouped, given the potential impact they can have on the rider's manoeuvres. In this analysis, the number of lanes is grouped into one lane, two lanes, and more than two lanes; accidents on two lanes were prevalent, accounting for 55 %. Finally, most accidents occurred on municipal roads, accounting for around 72%.

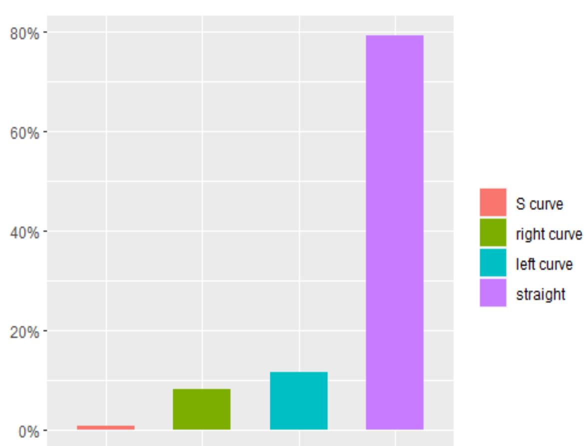

Figure 48: percentage of EDPm accidents by curvature types.

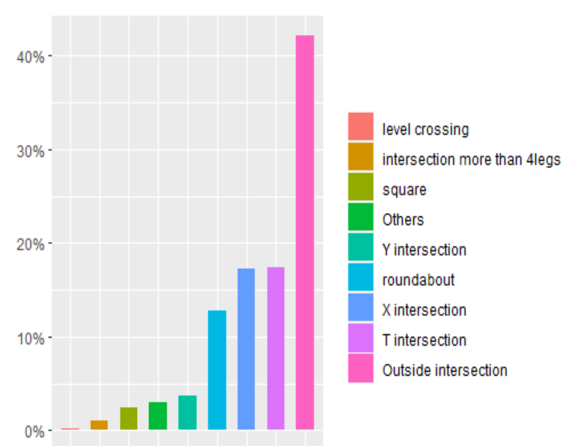

Figure 49: percentage of EDPm accidents by intersections.

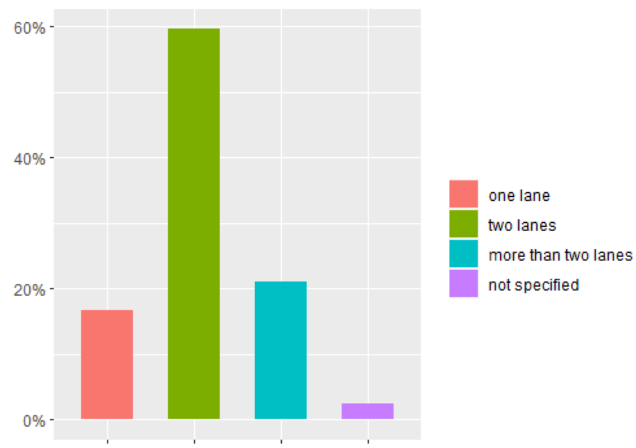

Figure 50: percentage of EDPm accidents by lanes number.

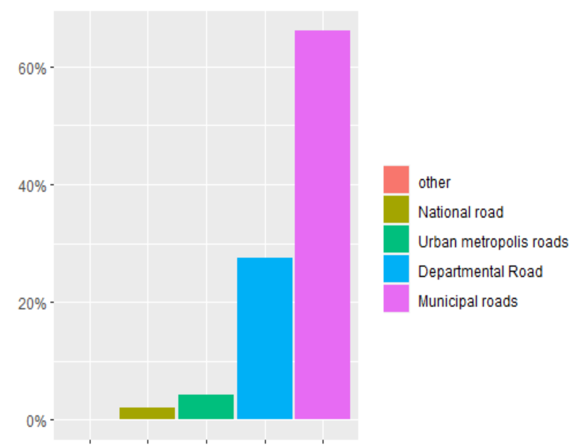

Figure 51: percentage of EDPm accidents by road type.

4.1.5.3.3. Collision characteristics

The French dataset provides detailed information on collision characteristics and the object involved, whether moving or stationary. As shown in Figure 52, side collision was the most frequent type, 62 %, followed by accident without collision, around 12%; frontal, 11%, rear 6%; multiple and series collisions were rare, and other types of collisions differently from the previously mentioned accounting for 9 %. Regarding moving objects, EDPm accidents with motor vehicles were predominant, accounting for approximately 80% of the accidents (see Figure 53).

When examining EDPm accidents with fixed objects, as shown in Figure 54, there is a substantial lack of data as in the case of e-bike accidents. For instance, accidents with fixed objects such as walls, bridge piers, urban furniture, post singe, objects on the sidewalk or shoulder, parked vehicles, and existing roads without obstacles combined were accounted for approximately 10% of accidents, around 90% of accidents identified as none this rise the concern about the quality of data.

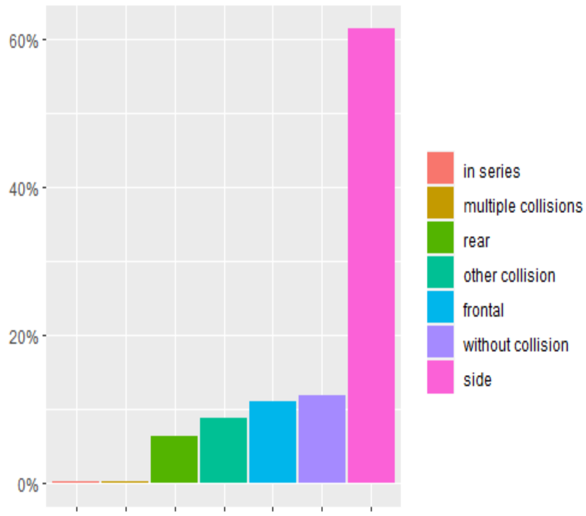

Figure 52: percentage of EDPm accidents by collision type.

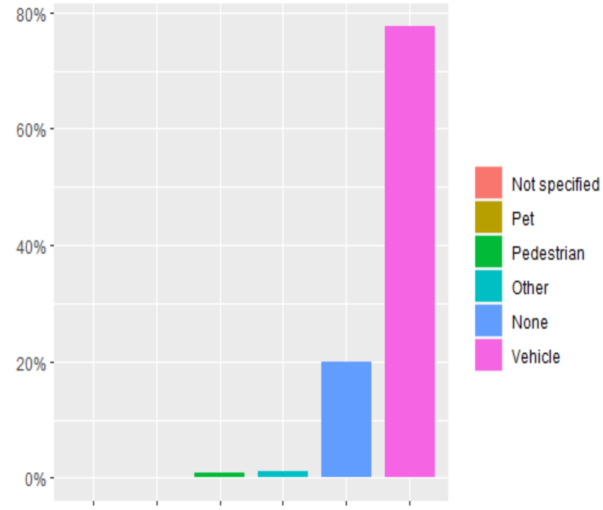

Figure 53: percentage of EDPm accidents by moving obstacles.

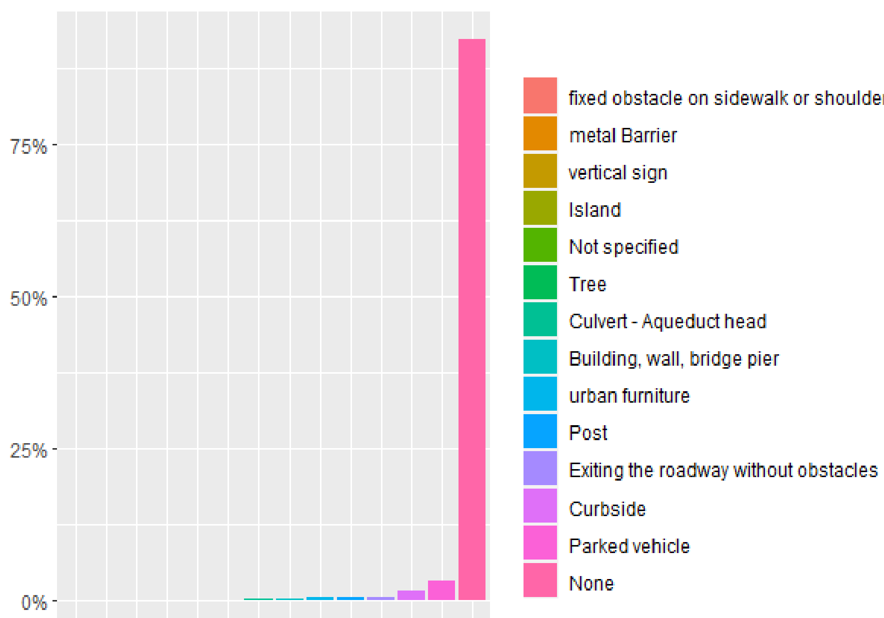

Figure 54: percentage of EPDm accidents by fixed obstacles.

4.2. Methods

4.2.1. Random forest: an introduction

Machine learning models do not rely on predetermined correlations, unlike statistical models, which require a predetermined relationship between dependent and independent variables [77]. Therefore, they are becoming increasingly popular in this field of study. The random forest algorithm introduced by Leo Breiman in 2001 [78] was selected to develop a random forest model to classify the severity levels of e-bike and e-scooter accidents in France and Belgium. The selection of random forest is based on its capability to ensure high models' performance even when dealing with imbalanced data distribution [11], [77], which are common characteristics of road traffic accidents. The data imbalance refers to one class being more frequent than another. In addition, the random forest has decent resistance to outliers [79].

Random forest models are ensemble techniques for classification, which are based on subdividing the data into different samples, and a unique decision tree is constructed from each sample [80]. The decision trees are developed based on the splitting rule. Several splitting criteria can be used (e.g., Gini index, Gain Ratio) [80]. In our models, we used the Gini index because it provides robust models [81]. The Gini index measures the impurity of an attribute with respect to the classes [80]. The splitting of each tree node is made based on the Gini index. The process is recursively maintained until we reach the maximum depth of splitting [80]. This process is applied to each tree, and the final class prediction is the option that receives the most significant number of votes from each decision tree in the forest [80]. In this study we built the random forest model using the R programming language.

Because the random forest is built from a decision tree, understanding the decision tree model aids in understanding it. Generally, constructing a decision tree model involves three steps [106]:

1- identify the goal (target variable) and the factors influencing it (attribute variables) [106].

2- Applying splitting algorithm on the attribute variables, the dataset breaks down into child nodes [106].

3- Further splitting applies for each child node, which means each node is treated as a parent node [106].

One key aspect of the decision tree model is the use of different algorithms for splitting. This not only showcases the depth and versatility of the technique but also ensures that each child node is as homogenous as feasible after the splitting [106]. Figure 55 shows the Decision tree structure whereas, the terminal node in the figure represents the predicted class [106].

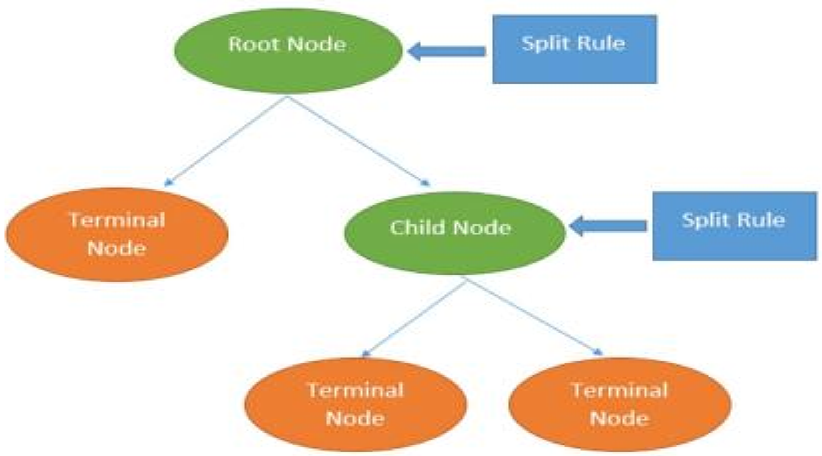

Figure 55: Decision Tree structure.
Source: Xiaoyi Zhou, Pan Lu, Zijian Zheng, Denver Tolliver, Amin Keramati, 2020.

In summary, building a random forest model requires ensemble techniques based on subdividing the dataset into several portions, and for each portion, a unique decision tree is constructed; the result obtained from this process is a collection of diverse decision trees [107]. Ultimately, the final class assignment is determined by a majority vote amongst the predictions from all the individual trees within the forest [107]. Figure 56 shows how the last class prediction of a random forest is determined. The final class prediction is the option that receives the most significant number of votes from each decision tree in the forest [106].

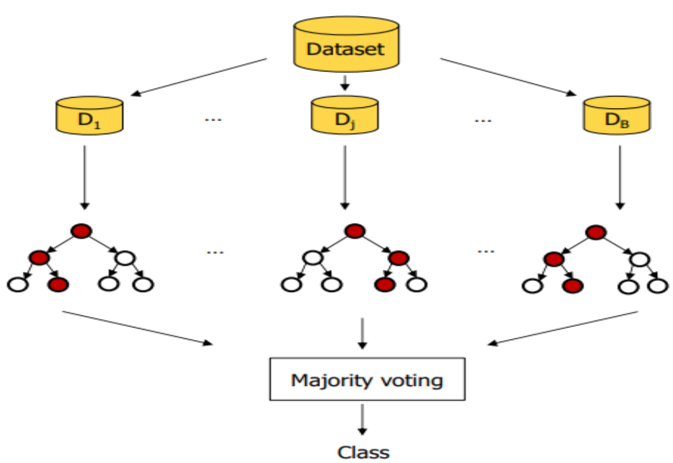

Figure 56: Random Forest structure.
Source: Tan,Steinbach, Kumar, Introduction to Data Mining, McGraw Hill 2006

4.2.2. Building random forest model: methods

4.2.2.1. Data splitting and utilization for building and evaluating the random forest model

Data preparation is essential for building a machine-learning model [75]. The model's performance is significantly affected by the quality of the data [75]. Several data preprocessing techniques were implemented before building the model; these include data cleaning and aggregation of the attribute values. Data cleaning represents handling the missing value; in our analysis, we removed the accidents when we observed missing attribute values. Regarding attribute aggregation, we aggregate the attribute values whenever the distribution of the accidents by that attribute value is less frequent.

Building an effective random forest model entails several stages, such as selecting variables, tuning parameters, and evaluating model performance. Therefore, utilizing the available data to enhance the model's effectiveness is essential. The data is split into two parts. Most of the data is used to build the model, and the remaining is used to evaluate the model.

The most common technique for utilizing the data involved the use of simple random samples [108]. While simple random sampling is appropriate for many scenarios, there are instances where it may not be optimal [108], specifically when dealing with classification tasks characterized by imbalanced classes, where a particular class is less frequent than others [108].

Considering that our analysis relies on classifying the severity levels from accident data with accidents being rare events, it is more likely to have an imbalance class distribution among the data; thus, applying simple random sampling might result in a bias towards the more frequent class [108]. To overcome the issue of imbalanced classes, we apply the stratified sampling method. Stratified random sampling begins by dividing the population into distinct groups, or strata, based on predetermined criteria. Within each stratum, samples are then randomly selected [109]. Additional technique to overcome the class imbalance issue is the implementation of Synthetic Minority Oversampling Technique (SMOTE).

The Synthetic Minority Oversampling Technique (SMOTE) was implemented through the R programming language to overcome the issue related to class imbalance. The SMOTE technique is commonly used in machine learning algorithms to balance data [76]. It generates new minority features by creating synthetic incidences (new data). The new data is generated by interpolating between neighbouring minority class instances while retaining the original features [76].

4.2.2.2. Resampling technique through cross validation and the estimation of model hyper-parameters

The resampling method is an iterative technique applied only to the training data [108]. For each iteration of the resample, the data is subdivided into the analysis and assessment sets see (Figure 57).

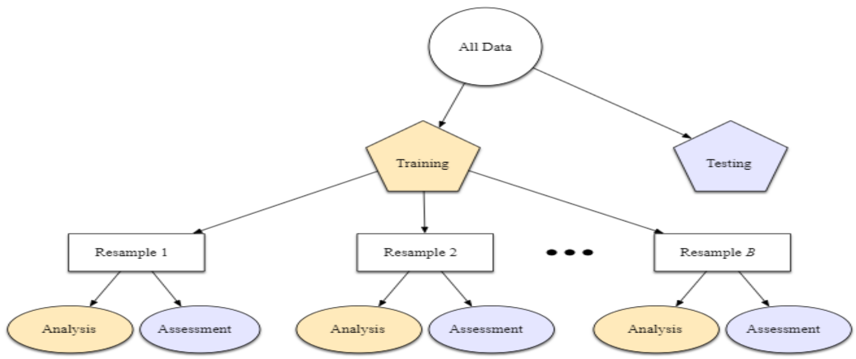

Figure 57: Resampling structure.
Source: Source: Max Kuhn, Julia Silge, 2023.

In our model, the cross-validation method was the resampling technique for constructing the Random Forest (RF) model. This approach divides the dataset into K sets of approximately equal size (called folds); the k-fold cross-validation method extends this principle by dividing the data into k partitions of equal size. Throughout each iteration, one partition allocates for testing, and the remaining partitions serve for training; the process repeated several times [107] see (Figure 58). In our models, a value of 10 folds was chosen for the K parameters.

Figure 58: cross validation.

Estimating the tuning parameters, also known as hyperparameters a priori, is crucial since they cannot be obtained from the training set; these parameters directly influence the model performance and its ability to predict the correct classes [108]. These parameters include the following: "n_*tree*," represents the number of trees utilized in constructing the model, "*mtry*," which indicates the number of predictor columns randomly sampled for each split in the tree, and "*min_n*" representing the minimum number of data points necessary to execute a split in a tree-based model [108]. The specific values of these hyperparameters obtained through tuning for each country's dataset will be detailed later in this Chapter. also, cross-validation is employed to further refine the effectiveness of the hyperparameters by estimating the tuning parameters for each fold and see what are the optimal values that the model can obtain.

4.2.2.3. Model evaluation

To evaluate the performance of the random forest model in correctly identifying the predicted classes, we used the following performance measures: accuracy, precision, recall, and F1 based on the confusion matrix. The confusion matrix as illustrated in Table 7 [107]. provides a concise overview of the instances classified correctly or incorrectly by a classification model. We obtained the confusion matrix from R programming language.

	Predicted class	
Actual class	True positive (TP)	False negative (FN)
	False positive (FP)	True negative (TN)

Table 7: Confusion matrix.
Source: Tan,Steinbach, Kumar, Introduction to Data Mining, McGraw Hill 2006

Where the following definitions apply:

- True positive (TP): number of positive classes correctly predicted by the model.
- False Negative (FN): the number of positive classes wrongly predicted as negative by the model.
- False positive (FP): the number of negative classes wrongly predicted as positive by the model.
- True negative (TN): the number of negative classes correctly predicted by the model.

From the confusion matrix the following performance measurement metrics are calculated:

$$accuracy = \frac{TP + TN}{TP + TN + FN + FP} \tag{1}$$

accuracy represents the ratio of correctly classified class to the total classes in the dataset. It is important to remember that although accuracy is still a commonly used performance indicator in the literature, imbalanced data may compromise its validity. Imbalanced data occurs when one class significantly outnumbers the other. In such cases, accuracy can be misleading as it may overemphasize the performance of the majority class while overlooking the classification accuracy of the minority class [107]. Therefore, other measures such as sensitivity, precision, recall, and F- measure should be calculated [106].

Sensitivity, as illustrated in equation (2), measures the model's effectiveness based on how the model predicts well the positive class when the actual outcome is positive [110]

$$Sensitivity = \frac{TP}{TP + FN} \quad (2)$$

Specificity, also known as recall, as defined in equation (3), measures the model's effectiveness in predicting the negative class when the actual outcome is negative. As illustrated in equation (4), Precision defines how good a model is at predicting the positive class [110]. Its asses the percentage of correct positive predictions about the total positive predictions provided by the model [106].

$$\text{specificity} = \text{Recall} = \frac{TN}{TN + FP} \quad (3)$$

$$\text{Precision} = \frac{TP}{TP + FP} \quad (4)$$

Finally, Precision and recall can be combined into another metric known as F1- measure, which is considered as harmonic mean between the recall and precision see equation (5) [107].

$$F1 = 2 * \frac{recall * precision}{recall + precision} \quad (5)$$

4.2.2.4. Results (variables Importance)

In Random Forest, the Gini index indicates which variables are the most important for correctly classifying data and, as a result, are more influential in the model decision-making [11]. The Gini index indicates the probability of splitting a randomly selected attribute from the sampled dataset [82]. The higher the Gini index, the higher the likelihood of that selected attribute to be split [82]. The Gini index is calculated using equation (6) [82].

$$Gini\ index = \sum_{k=1}^{k} P_k (1 - P_k) = 1 - \sum_{k=1}^{k} P_k^2 \quad (6)$$

Whereas:

K= represents the classes in the dataset.[82]

P_k= the probability of that selected attribute to belong to class k.

This study uses the Gini index through R programming to determine the important variables that influence the severity levels of e-bike and e-scooter accidents based on the random forest-trained models.

4.2.3. Building the random forest model for micro-mobility accidents in France and Belgium using R programming

The aim of developing a random forest model for micro-mobility accidents in France and Belgium is to identify the variables related to user characteristics, infrastructure characteristics, and collision characteristics that affect the severity levels resulting from micromobility accidents. In other words, our dependent variables are the accident severity levels, and our independent variables are variables related to users, infrastructure, and collision characteristics.

The procedures for building a random forest model in R entail several stages. In order to perform each stage, several packages must be installed. Table 8 shows the packages and the functions that were utilized in building the random forest model.

Application	Packages	Function
Data splitting	rsample	intial_split
Resampling technique with cross validation	rsample	Vfold_cv
Preprocessing and recipe	recipes	recipes
Estimation of hyper parameters	usemodels, tune	Show_best
Random forest model	parsnip	Random_forest
Confusion Matrix	yardstick	conf_mat
Variables importance	Vip	Vip

Table 8: packages and function utilized in building the random forest model in R programming.

Firstly, we split the data; the dataset is divided into a training set and a testing set. Most of the data was utilized to build the model, and the remaining to validate the model. The stratified random sampling technique is implemented by dividing the population into distinct groups or strata, and then, within each group, samples are randomly selected. The stratified sampling technique is performed in R programming with the (initial_split) function, which is provided in the R environment from the (rsample) package, utilizing the following syntax: initial_split (data, strata = severity_levels); here, the term "severity level" refers to the class targeted for prediction by the Random Forest model.

Secondly, we perform the resampling technique through the cross-validation method; we apply K-fold cross-validation on the training set, which divides the training data into K equally sized folds. Each fold is used as a validation set, while the remaining K-1 folds serve as the training set. The cross-validation is repeated K times, ensuring that every data point is used for training and validation. To perform such a technique in R, the function (vfold_cv) is provided as part of the (rsample) package, is used.

Thirdly, we perform the data preprocessing by using the (recipe) function from the (recipe) package, which allows us to convert all the categorical variables to dummy variables in the algorithm, which helps the effectiveness of the algorithm before training the model. In addition, the generation of the synthetic features using SMOTE (Synthetic Minority Over-sampling Technique) is made as part of the data preprocessing through the recipe function using the function (step_smote) to overcome the issue related to a class imbalance in the severity levels, which is common in road accidents data, this ensures that the model receives a balanced input, which improves the prediction accuracy.

Fourthly, for estimating the hyperparameters (tuning), the (usemodels) package takes the data frame and model formula, then writes out R code for tuning the model. The code also creates an appropriate recipe whose steps depend on the requested model and the predictor data. The suggested code by R is used to find the optimal value of model hyperparameters. After that, we extract the following hyperparameter values (mtry), the number of predictor columns randomly sampled for each split in the tree, and (min_n), the minimum number of data points necessary to execute a split in a tree-based model.

Finally, the model is evaluated using the confusion matrix obtained through the function (conf_mat) provided by the (yardstick) package. Moreover, the functions provided by the package (Vip) are used to extract the important variables that affect the severity levels of accidents.

4.2.4. Random forest for e-bike accidents in France

4.2.4.1. Definition of the variables used for building the random forest model

4.2.4.1.1. Severity levels of the accidents

Figure 59 shows the percentage of severity levels resulting from e-bike accidents in France in 2022; most e-bike riders sustained a slight injury of 70%, 22% experienced serious accidents, while fatality accounted for 8%. These three severity level classes are then grouped to develop a random forest model containing two classes (serious & fatal) accidents and (minor) accidents. After this grouping for the severity levels, we obtain 70% of (minor) accidents and 30% of (serious & fatal) accidents (see Figure 60)

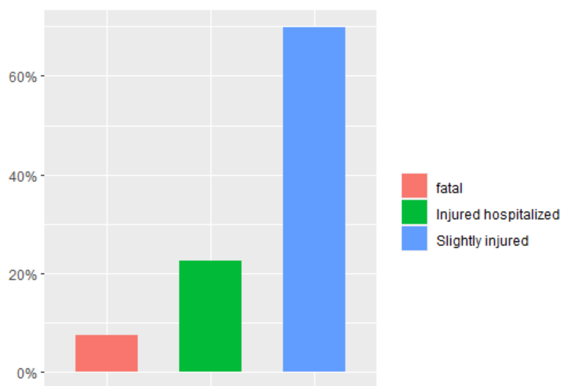

Figure 59: percentage of e-bike accidents by severity levels.

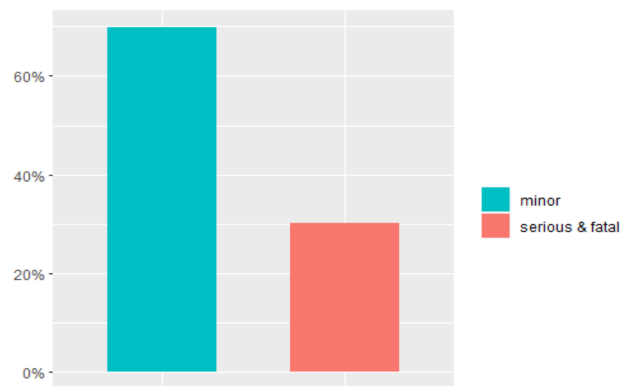

Figure 60: percentage of converted severity levels.

4.2.4.1.2. User characteristics and trip characteristics

Table 9 contains attributes and the attribute values regarding the user and trip characteristics, as well as the percentage of accidents severity levels utilized in building the random forest model. User characteristics include two attributes: gender and age group; the model distinguishes between two categories for gender, male and female, while for age group, we consider two age classes: a reference category ranging from 14 years to 60 years and senior riders with age over 60 years.

Regarding safety equipment, the model utilizes four classes: helmets, reflective vests, instances where there is no safety equipment and others; the category other represents the types of safety equipment different from the previously mentioned. No aggregation has been applied for trip purpose, as detailed in Table 9. Concerning the timing of accident occurrences, our examination classifies these instances into three temporal categories:

morning (6 AM to 2 PM), evening (3 PM to 11 PM), and night (from midnight to 5 AM), as indicated in Table 9.

Variables	Categories	Total (column %)	Severity levels (row %)	
			Serious &fatal	Minor
Gender	Male	355 (65%)	106 (30%)	249 (70%)
	Female	193 (35%)	57 (30%)	136 (70%)
Total %		(548) (100%)	163 (30%)	385 (70%)
Age group	Reference category	425 (78%)	96 (23%)	329 (77%)
	Senior	123 (22%)	67 (54%)	56 (46%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Trip purpose	Home - work	176 (32%)	32 (18%)	144 (82%)
	Home - school	7 (1%)	0 (0%)	7 (100%)
	Leisure	202 (37%)	98 (49%)	104 (51%)
	Purchase	9 (2%)	4 (44%)	5 (56%)
	Other	72 (13%)	7 (10%)	65 (90%)
	Not specified	82 (15%)	22 (27%)	60 (73%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
The use of safety equipment	Helmet	255 (47%)	78 (31%)	177 (69%)
	Reflective vest	5 (1%)	4 (80%)	1 (20%)
	No equipment	89 (16%)	50 (56%)	39 (44%)
	Other	199 (36%)	31 (16%)	168 (84%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Time range	Morning	271 (50%)	82 (30%)	189 (70%)
	Evening	254 (46%)	77 (30%)	177 (70%)
	Night	23 (4%)	4 (17%)	19 (83%)

Variables	Categories	Total (column %)	Severity levels (row %)	
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**

Table 9: user characteristics and the percentage of severity levels for e-bike accidents in France.

4.2.4.1.3. Infrastructure characteristics

Table 10 shows eight attributes concerning the infrastructure characteristics and percentage of accident severity levels used in building the random forest model. Regarding land use patterns, two attribute values are considered accidents occurring in urban and non-urban areas. For accident location, the model distinguishes between accidents occurring on road lanes and cycle lanes, and categories are different from road lanes and cycle lanes donated, as others.

The road speed limit includes three attribute values: either lower than 50 km/h, exceeding 50 km/h, and none. In addition, to investigate the importance of using the e-bike light in the environment surrounding the accident location, lighting conditions are considered in two classes: whether the accident occurred in daylight or at night.

Regarding the road curvature, we consider two attribute values, straight road and not straight road, such as curves grouped in one attribute value donated as other. Additionally, the number of lanes is considered in the model calibration as follows, with categories including one lane, two lanes, and more than two lanes, and not specified.

In terms of intersection, we used these five attribute values outside intersection, X intersection, T intersection, and other types of interaction; we grouped them into "others." In addition, three attribute variables are considered for the road category: municipal roads, departmental roads, and other road types, we aggregate them into single attribute values donated as "other."

Variables	Categories	Total (column %)	Severity levels (row %)	
			SERIOUS & FATAL	MINOR
Urban none- urban	Outside urban areas	82 (15%)	56 (68%)	26 (32%)
	In urban areas	466 (85%)	107 (23%)	359 (77%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Accident location	On road lane	408 (74%)	139 (34%)	269 (66%)
	On cycle path	110 (20%)	16 (15%)	94 (85%)
	Other	30 (6%)	8 (27%)	22 (73%)

Variables	Categories	Total (column %)	Severity levels (row %)	
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Intersections type	Outside intersections	228 (42%)	81 (36%)	147 (64%)
	X intersection	94 (17%)	15 (16%)	79 (84%)
	T intersection	98 (18%)	24 (24%)	74 (76%)
	Roundabout	71 (13%)	28 (39%)	43 (61%)
	Other	57 (10%)	15 (26%)	42 (74%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Road category	National road	12 (2%)	5 (42%)	7 (58%)
	Departmental road	153 (28%)	77 (50%)	76 (50%)
	Municipal road	359 (66%)	72 (20%)	287 (80%)
	Urban metropolis road	23 (4%)	9 (39%)	14 (61%)
	Other	1 (0%)	0 (0%)	1 (100%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Lighting condition	Daylight	413 (75%)	129 (31%)	284 (69%)
	Night	135 (25%)	34 (25%)	101 (75%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Curve type	Straight	435 (79%)	107 (25%)	328 (75%)
	Curve	113 (21%)	56 (50%)	57 (50%)
Total %		548 (100%)	163 (30%)	385 (70%)
Number of lanes	One lane	91 (17%)	23 (25%)	68 (75%)
	Two lanes	325 (59%)	121 (37%)	204 (63%)
	More than two lanes	118 (22%)	16 (14%)	102 (86%)
	Not specified	14 (2%)	3 (21%)	11 (79%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Road speed limit	Lower than 50 km/h	475 (87%)	111 (23%)	364 (77%)
	Higher than 50km/h	66 (12%)	47 (71%)	19 (29%)

Variables	Categories	Total (column %)	Severity levels (row %)	
	None	7 (1%)	5 (71%)	2 (29%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**

Table 10: infrastructure characteristics and the percentage of severity levels for e-bike accidents in France.

4.2.4.1.4. Collision characteristics

Table 11 contains the two attributes utilized in the model regarding collision types and the percentage of accident severity levels. Specifically, two variables define collision types: side collisions and "other." Similarly, in instances where a moving object is involved in the accident, the two variables considered are accidents with vehicles and "other" grouped other moving objects. Notice that there is no consideration for accidents involving fixed obstacles; the descriptive analysis has indicated the absence of valuable variables within the dataset.

Variables	Categories	Total (column %)	Severity levels (row %)	
			Serious & fatal	Minor
Collision type	Side	330 (60%)	80 (24%)	250 (76%)
	Other	218 (40%)	83 (38%)	135 (62%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**
Accident with moving obstacle	Vehicle	428 (78%)	111 (26%)	317 (74%)
	Other	120 (22%)	52 (43%)	68 (57%)
Total %		**548 (100%)**	**163 (30%)**	**385 (70%)**

Table 11: collision characteristics and the percentage of severity levels for e-bike accidents in France.

4.2.4.2. Process of building and validating the random forest model for e-bike accidents in France using R programming

4.2.4.2.1. Modelling process

The mentioned variables in Table 9, Table 10, and Table 11 are used in developing and validating the random forest model for e-bike accidents in France with severity levels as dependent variables using R programming. We split the data into training (80%) and testing (20%); however, the testing data was not seen by the model in order to evaluate the model's performance correctly. Also, the cross-validation technique is used in the training set; the training set is divided into 10 equal folds, and in each iteration, one-fold is kept for testing and the remaining for training the model.

illustrates that the e-bike accident data in France shows an imbalance class issue, as previously noted, with (minor) accidents being more frequent than (serious & fatal). To overcome the issue related to class imbalance, we used the SMOTE technique (Synthetic Minority Over-sampling Technique) to generate synthetic features from the less frequent class.

In addition, to optimize the model performance, we used the tuning hyperparameters technique. Notice that one parameter that does not require tuning is the number of trees, as it is selected randomly. Throughout our experimentation, we tested different values and determined that the optimal value for this parameter was 50. For the other parameters, the following values have been assigned to each parameter (see Figure 61).

- Ntree = 50
- Mtry = 7
- Min_n = 32

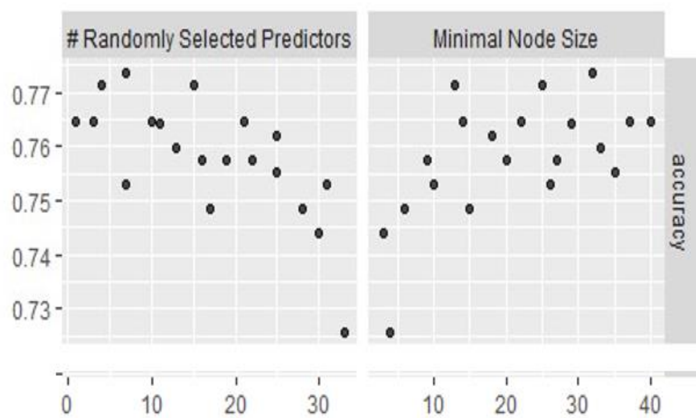

Figure 61: the model hyperparameters resulting from tuning for e-bike accidents in France.

Subsequently, by using the above hyperparameter values, we build the random forest model using the training data. The predicted class resulting from the model is summarized in Table 12, which represents the confusion matrix. As shown in Table 12, the model correctly predicts 259 minor accidents (true positive) and 77 serious and fatal accidents (true negative).

In addition, the model wrongly predicted 53 accidents as serious and fatal, which are minor (false negative); however, our goal is to improve safety, and predicting minor accidents as serious and fatal lies with our objective. Although the model wrongly predicted 49 accidents as minor accidents (false positive), which are serious and fatal, this wrong prediction of the serious and fatal accident can be accepted given the imbalanced nature of the data.

	Truth class		
predicted class		minor	serious & fatal
	Minor	259	53
	serious & fatal	49	77

Table 12: confusion matrix for trained random forest model for e-bike accidents in France.

4.2.4.2.2. Model validation

We utilized a portion of the data (20%) to correctly assess the model's reliability; the test set results are then summarized in Table 13 (the confusion matrix). The diagonal elements of this matrix, as shown in Table 13, represent the count of correctly classified accidents for each category of injury severity levels. In contrast, the off-diagonal elements represent the count of misclassified accidents.

	Truth class		
predicted class		minor	serious & fatal
	Minor	69	12
	serious & fatal	8	21

Table 13: confusion matrix resulting from the test set for e-bike accidents in France.

The confusion matrix's result is used to calculate the following performance measures: recall, Precision, and F1-measure. We apply equations (3), (4), and (5), which were previously mentioned in this Chapter due to the imbalance classes in the data. We calculate performance measurements for both classes: minor accidents and serious and fatal accidents.

The Precision represents the proportion of minor accidents classified as minor (out of all accidents predicted as minor). In this case, the Precision is 90%. The recall represents the model's ability to identify actual minor accidents. A recall of 85% indicates that the model captured 85% of all minor accidents. Finally, we calculate the harmonic mean using the F1 measure, combining the Precision and recall and balancing their importance. A value of 88% has been found for the F1-measure. Similarly, the same calculation is applied to serious and fatal classes, resulting in a recall of 72% and a precision of 64%. Finally, the harmonic mean (F1-measure) combining the Precision and recall is 68%.

4.2.5. Random forest model for e-bike accidents in Belgium

The aim of building a random forest model for e-bike accidents in Belgium is the same as in the case of France, which is to determine the severity levels resulting from e-bike accidents. However, unlike the French model, in the Belgian model, the severity levels are defined as injuries and no injuries, and the reason behind that is related to the nature of the Belgian data. As stated earlier in this Chapter, the Belgian data provides the severity levels for each individual involved in an accident where at least one e-bike was involved.

Our assumption is based on the fact that when e-bike users are involved in an accident with other types of vehicles, they are more likely to sustain an injury due to reduced protection compared to other types of vehicles. This assumption is validated when examining the Belgian data 95% of e-bike users involved in the accident sustain an injury which is within these three classes (slight injury, serious injury, and fatality). Also, when excluding e-bike users involved in the accidents and examining other road users involved with e-bike accidents, nearly 90% of such users did not sustain any injuries. In summary, the injured classes which will be predicted by the model are more likely to be an e-bike user. Applying such an assumption in building the random forest model will have considerable benefits in overcoming the class imbalance problem, which is common among road accidents.

4.2.5.1. Definition of the variables used for building the random forest model

4.2.5.1.1. Accidents severity levels

Figure 62 shows the percentage of severity levels for individuals who were involved in a road accident where at least one e-bike was present. Nearly 44% of individuals did not experience injuries, approximately 48% sustained slight injuries, 7% were seriously injured, and 1% died within 30 days after the accidents. These four severity levels resulting from the accidents are then converted to two classes, injured and uninjured, to obtain the dependent variables that need to be predicted by the random forest model (see Figure 63)

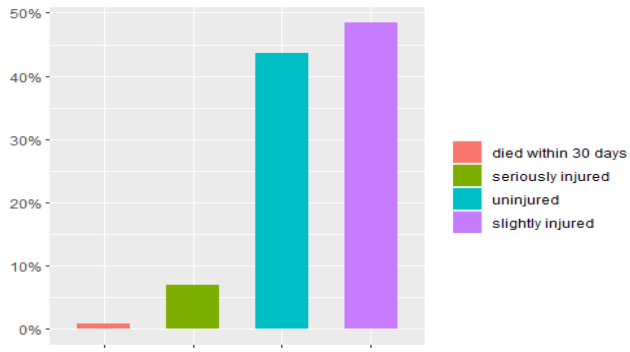

Figure 62: percentage of severity levels of individuals involved in e-bike accidents.

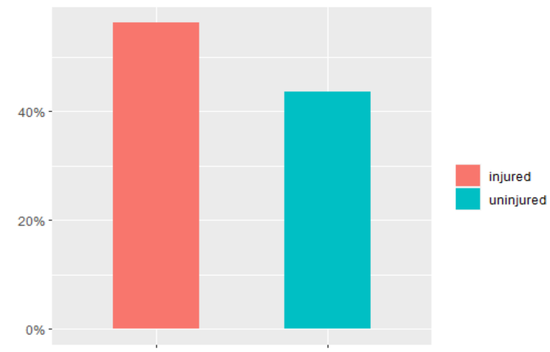

Figure 63: percentage of (injured & uninjured) individuals involved in e-bike accidents.

4.2.5.1.2. User characteristics

Table 14 illustrates the attributes related to user characteristics and their corresponding values used in building the random forest model for individuals involved in e-bike accidents in Belgium. Concerning gender, three attribute values are defined as male, female, and unknown. Based on the descriptive analysis, the age group is discretized to individuals from 0 to 14 years,15 to 49 years, 50 to 69 years, and above 70 years.

Variables	**Categories**	**Total (column %)**	**Severity levels (row %)**	
		Category total	Injured	Uninjured
Gender	Male	11568 (55%)	5621 (49%)	5947 (51%)
	Female	9445 (45%)	6243 (66%)	3202 (34%)
	Unknown	74 (<1%)	23 (31%)	51 (69%)
Total %		**21,087 (100%)**	**11,887 (56%)**	**9,200 (44%)**
Age group	0 to 14 years old	700 (3%)	331 (47%)	369 (53%)
	15 to 49 years old	10420 (49%)	4877 (47%)	5543 (53%)
	50 to 69 years old	6843 (32%)	4451 (65%)	2392 (35%)
	+70 years old	3124 (15%)	2228 (71%)	896 (29%)
	Total %	**21,087 (100%)**	**11,887 (56%)**	**9,200 (44%)**

Table 14: user characteristics and the percentage of severity levels for e-bike accidents in Belgium.

4.2.5.1.3. Infrastructure characteristics

Table 15 illustrates the attributes and their corresponding values concerning the infrastructure characteristics used in building the random forest model. Regarding the infrastructure features, we define 8 attribute values, representing all the attributes presented in the available dataset without aggregating them.

Also, the dataset provides 8 attribute values regarding the biker's position in terms of being in a separated cycle lane, a cycle lane marked on the ground, a suggested cycle lane, riding on the main carriageway, none of the previously mentioned positions, and not applicable. Notice that the attribute value (not applicable), representing individuals differently from e-bike users since the dataset contains all individuals involved in e-bike accidents, as previously noted.

Variables	**Categories**	**Total (column%)**	**Severity levels (row %)**	
			Injured	Uninjured
Local conditions	Roundabout	935 (4%)	472 (50%)	463 (50%)
	Level crossing	106 (<1%)	59 (56%)	47 (44%)
	Tunnel	88 (<1%)	72 (82%)	16 (18%)
	Bridge, viaduct	512 (2%)	300 (59%)	212 (41%)
	Building site/works affecting the roadway	145 (<1%)	108 (74%)	37 (26%)
	Building site/works affecting the roadway + bridge, viaduct	2 (<1%)	2 (100%)	0 (0%)
	None of the above	14943 (71%)	8430 (56%)	6513 (44%)
	Unknown	4356 (21%)	2444 (56%)	1912 (44%)
Total%		**21,087 (100%)**	**11,887 (56%)**	**9,200 (44%)**
Biker position	On a cycle lane marked on the ground	4,422 (21%)	4,107 (93%)	315 (7%)
	On or off the carriageway	1,141 (5%)	1,056 (93%)	85 (7%)
	Riding on cycle lane separated from carriageway	2,377 (11%)	2,094 (88%)	283 (12%)
	Riding on or leaving the suggested cycle lane	399 (2%)	372 (93%)	27 (7%)
	None of the above	4,178 (20%)	3,800 (91%)	378 (9%)
	Not applicable (not a moped rider/cyclist)	8,570 (41%)	458 (5%)	8,112 (95%)
	Suggested cycle lane, against the flow of traffic	63 (<1%)	54 (86%)	9 (14%)
	Suggested cycle lane, normal traffic flow	633 (3%)	595 (94%)	38 (6%)

Variables	Categories	Total (column%)	Severity levels (row %)	
Total%		**21,087 (100%)**	**9,887 (47%)**	**9,200 (43%)**

Table 15: infrastructure characteristics and the percentage of severity levels for e-bike accidents in Belgium.

4.2.5.1.4. Collision characteristics

Table 16 shows two attributes regarding the collision characteristics and their corresponding values. Notice that the Belgian dataset includes fixed obstacles, pedestrians, and accidents without collision within the collision types. 9 attribute values are used in building the model, including driver-to-driver collisions such as head collisions, rear collisions, side collisions, etc., as shown in Table 16.

Concerning the individual involved, 21 vehicle types are used in the model, as well as two attribute values categorized as other road users, which represent different types of road users from the 22 vehicle types reported in Table 16 , and unknown, which represent the absence of such information related to individuals involved. Finally, the victims involved are defined by three classes: drivers, passengers, and other victims.

Variables	Categories	Total (column%)	Severity levels (row %)	
			Injured	Uninjured
Collision type	Between 2 drivers: from the side (front/back/side)	11,933 (57%)	5,959 (50%)	5,974 (50%)
	Between 2 drivers: head-on collision	2,584 (12%)	1,582 (61%)	1,002 (39%)
	Between 2 drivers: rear-end	1,460 (7%)	790 (54%)	670 (46%)
	Between 2 drivers: side against side	2,386 (11%)	1,281 (54%)	1,105 (46%)
	Chain collision (3 or more drivers)	90 (<1%)	50 (56%)	40 (44%)
	Single user, no obstacle (incl. Fall)	1,090 (5%)	1,033 (95%)	57 (5%)
	User against an obstacle located off the carriageway	318 (2%)	259 (81%)	59 (19%)
	User against an obstacle on the carriageway	343 (2%)	324 (94%)	19 (6%)
	With a pedestrian	883 (4%)	609 (69%)	274 (31%)
Total%		**21,087 (100%)**	**11,887 (56%)**	**9,200 (44%)**
User type	Bicycle	1,066 (5%)	649 (61%)	417 (39%)
	Bus	63 (<1%)	1 (2%)	62 (98%)
	Coach	13 (<1%)	0 (0%)	13 (100%)

Variables	Categories	Total (column%)	Severity levels (row %)	
	Electric bike	3,794 (18%)	3,653 (96%)	141 (4%)
	Electric bike (<=250w and <=25km/h)	7,370 (35%)	6,960 (94%)	410 (6%)
	Farm tractor	33 (<1%)	0 (0%)	33 (100%)
	Lorry	219 (1%)	0 (0%)	219 (100%)
	Minibus	16 (<1%)	0 (0%)	16 (100%)
	Mixed car	339 (2%)	3 (1%)	336 (99%)
	Moped	1 (<1%)	0 (0%)	1 (100%)
	Moped a (2 wheels)	130 (<1%)	68 (52%)	62 (48%)
	Moped b (2 wheels)	101 (<1%)	52 (51%)	49 (49%)
	Motorcycle (up to 400 cc)	50 (<1%)	26 (52%)	24 (48%)
	Motorcycle (over 400 cc)	33 (<1%)	12 (36%)	21 (64%)
	Motorised moving machine (<=18km/h)	16 (<1%)	12 (75%)	4 (25%)
	Passenger car	6,326 (30%)	67 (1%)	6,259 (99%)
	Pedestrian	457 (2%)	304 (67%)	153 (33%)
	Speed pedelec (<= 4000w and <=45km/h)	60 (<1%)	50 (83%)	10 (17%)
	Tractor + semi-trailer	92 (<1%)	1 (1%)	91 (99%)
	Tractor alone	8 (<1%)	0 (0%)	8 (100%)
	Van	795 (4%)	8 (1%)	787 (99%)
	Other road user	49 (<1%)	0 (0%)	49 (100%)
	Unknown	43 (<1%)	8 (19%)	35 (81%)
Total%		**21,087 (100%)**	**11,887 (56%)**	**9,200 (44%)**
Victim type	Driver	20,055 (95%)	11,745 (59%)	8,310 (41%)
	Passenger	1,002 (5%)	140 (14%)	862 (86%)
	Other victims	30 (<1%)	2 (7%)	28 (93%)
Total%		**21,087 (100%)**	**11,887 (56%)**	**9,200 (44%)**

Table 16: collision characteristics and the percentage of severity levels for e-bike accidents in Belgium.

4.2.5.2. Process of building and validating the random forest model for e-bike accidents in Belgium using R programming

4.2.5.2.1. Modelling process

The variables presented in Table 14, Table 15, and Table 16 are utilized in developing and validating the random forest model for all individuals involved in accidents where at least one e-bike was present with severity levels as dependent variables (injured and uninjured) using R programming. Differently from the random forest model that was previously built for e-bike accidents in France, in the Belgian model, the data split into (70%) for training the model and (30%) for testing due to a large number of observations in the Belgian dataset compared to the French dataset. In addition, the cross-validation technique is performed in the training set; the training set is partitioned into ten equal folds; in each iteration, one-fold is kept for testing and the remaining for training the model.

After that, we perform the tuning technique to obtain the optimal hyperparameters used in building the random forest model. Notice that there is no need for the SMOTE technique (Synthetic Minority Over-sampling Technique) to generate synthetic features, as in the case of France's e-bike model. We overcome the issue related to imbalanced data by applying the previous assumption to the accident severity levels. The hypermeter values extracted from the tuning have the following values (see Figure 64)

- Ntree = 200
- Mtry = 4
- Min_n= 33

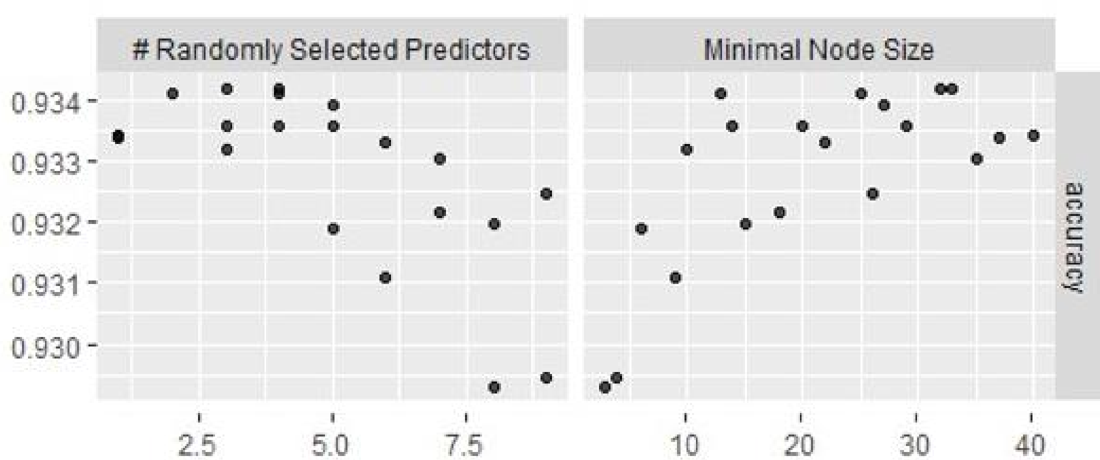

Figure 64: the model hyperparameters resulting from tuning for e-bike accidents in Belgium.

The result of predicted classes from the trained model is presented in Table 17 (the confusion matrix). The model is able to classify 8,643 as injured (true positive) and 6,137 as uninjured (true negative). However, the model misclassified 763 accidents involving injuries. Additionally, 272 accidents were uninjured, but the model classified them as injured.

Although the model misclassified some of the accidents, the result is highly accurate given the large amount of correctly classified accidents compared to misclassified ones.

	Truth class		
predicted class		injured	uninjured
	injured	8,643	763
	uninjured	272	6,137

Table 17: confusion matrix for trained random forest model for e-bike accidents in Belgium.

4.2.5.2.2. Model validation

In the Belgian model, we used 30% of the data to test the model due to the high number of observations we have compared to French data. Also, the classes are slightly balanced; therefore, we used the accuracy measure to assess the model reliability by applying equation (1) on the confusion matrix resulting from the test set, as shown in Table 18. We obtained an accuracy equal to 93% for injured classes. This high value of accuracy indicates that the model is highly effective in identifying injured classes resulting from e-bike accidents.

	Truth class		
predicted class		injured	uninjured
	injured	2,869	255
	uninjured	103	2,045

Table 18: confusion matrix for testing random forest model for e-bike accidents in Belgium.

4.2.6. Random forest model for e-scooter accidents in France

4.2.6.1. Definition of the variables used for building the random forest model

As mentioned, French traffic law categorizes e-scooters as motorized personal travel vehicles. Thus, the data concerning e-scooter accidents did not distinguish them from other motorized personal travel vehicles EDPm (Engin de déplacement personnel motorisé). Therefore, developing a random forest model to define the severity levels of e-scooter accidents will encompass the severity levels of other motorized personal travel vehicles.

4.2.6.1.1. Accidents severity levels

The data concerning the EDPm accidents contains the following severity levels: injured, slightly injured, seriously injured, and fatality. However, the percentage of uninjured resulting from EDPm accidents was less than 2%; thus, we filter only the severity levels of the accidents we are interested in. Figure 65 shows the percentage of severity levels resulting from EDPm accidents in France in 2022; most EDPm users sustained a slight injury of 80%, 18% experienced serious injuries, while fatality accounted for 2%. These three severity level classes are then converted to build a random forest model containing two classes (serious & fatal), injuries and (minor) injuries. After this conversion for the severity levels, we obtain 80% of (minor) accidents and 20% of (serious & fatal) accidents (see Figure 66).

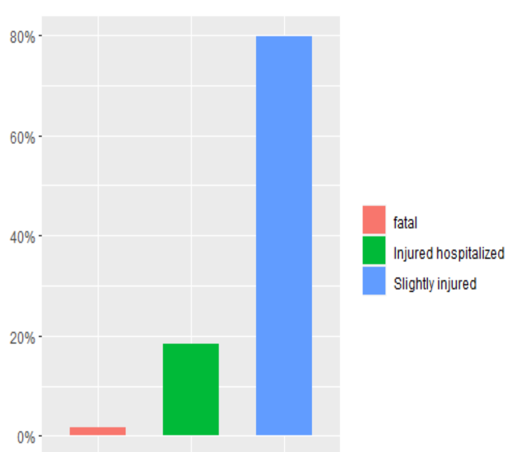

Figure 65: percentage of EPDm accidents by severity levels.

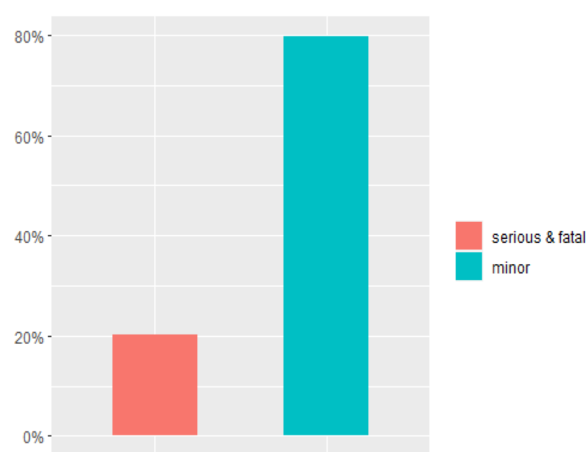

Figure 66: percentage of grouped severity levels (serious& fatal) and minor accidents.

4.2.6.1.2. User characteristics

Table 19 contains attributes and their corresponding values regarding the user and trip characteristics and the percentage of accident severity levels utilized in building the random forest model. User characteristics include gender and age group; the model distinguishes between two categories for gender, male and female. For the age group, we consider two age classes: a reference category over 16 years, which is the legal age for using an e-scooter in France, and a minor category representing users under 16 years.

Regarding safety equipment, the model utilizes four classes: helmets, reflective vests, instances where there is no safety equipment and others; the category other represents the types of safety equipment different from the previously mentioned. No aggregation has been applied for trip types, as detailed in Table 19. Concerning the timing of accident occurrences, our examination classifies these instances into four temporal categories: morning (7 PM to 3 PM), evening (4 PM to 8 PM), night (9 PM to 11 PM), and after midnight.

Variables	**Categories**	**Total (column%)**	**Severity levels (row %)**	
			Serious &fatal	Minor
Gender	Male	708 (78%)	160 (23%)	548 (77%)
	Female	288 (22%)	41 (14%)	247 (86%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Age group	Reference category	964 (97%)	191 (20%)	773 (80%)
	Minor category	32 (3%)	10 (31%)	22 (69%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Trip purpose	Home - work	255 (26%)	58 (23%)	197 (77%)
	Home - school	54 (5%)	6 (11%)	48 (89%)
	Leisure	255 (26%)	54 (21%)	201 (79%)
	Purchase	21 (2%)	8 (38%)	13 (62%)
	Other	127 (13%)	14 (11%)	113 (89%)
	Not specified	284 (28%)	61 (21%)	223 (79%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
The use of safety equipment	Helmet	254 (26%)	39 (15%)	215 (85%)
	Reflective vest	6 (<1%)	2 (33%)	4 (67%)

	No equipment	160 (16%)	64 (40%)	96 (60%)
	Other	570 (57%)	92 (16%)	478 (84%)
	Not specified	6 (<1%)	4 (67%)	2 (33%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Time range	Morning	464 (47%)	83 (18%)	381 (82%)
	Evening	348 (35%)	75 (22%)	273 (78%)
	Night	82 (8%)	14 (17%)	68 (83%)
	After midnight	102 (10%)	29 (28%)	73 (72%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**

Table 19: user characteristics and the percentage of severity levels EDPm accidents in France.

4.2.6.1.3. Infrastructure characteristics

Table 20 shows 8 attributes concerning the infrastructure characteristics and percentage of accident severity levels used in building the random forest model. Regarding land use patterns, two attribute values are considered accidents occurring in urban and non-urban areas. For accident location, the model distinguishes between accidents occurring on road lanes and cycle lanes, and categories are different from road lanes and cycle lanes donated, as others.

The road speed limit includes two attribute values: lower than 50 km/h, exceeding 50 km/h, and none where no information was present. In addition, to investigate the importance of using the e-scooter light in the environment surrounding the accident location, lighting conditions are considered in two classes: whether the accident occurred in daylight or at night.

Regarding the road curvature, we consider two attribute values, straight road and not straight road, such as curves grouped in one attribute value donated as other. Additionally, the number of lanes is considered in the model calibration as follows, with categories including one lane, two lanes, and more than two lanes, and not specified. In terms of intersection, we used these five

Variables	Categories	Total (column%)	Severity levels (row %)	
			Serious & fatal	Minor
Urban none- urban	Outside urban areas	43 (4%)	24 (56%)	19 (44%)
	In urban areas	953 (96%)	177 (19%)	776 (81%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Accident location	On road lane	784 (79%)	166 (21%)	618 (79%)
	On cycle path	134 (13%)	22 (16%)	112 (84%)
	Other	78 (8%)	13 (17%)	65 (83%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Intersections type	Outside intersections	404 (41%)	107 (26%)	297 (74%)
	X intersection	207 (21%)	30 (14%)	177 (86%)
	T intersection	168 (17%)	24 (14%)	144 (86%)
	Roundabout	111 (11%)	26 (23%)	85 (77%)
	Other	106 (11%)	14 (13%)	92 (87%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Road category	National road	7 (<1%)	2 (29%)	5 (71%)
	Departmental road	215 (22%)	63 (29%)	152 (71%)
	Municipal road	727 (73%)	124 (17%)	603 (83%)
	Urban metropolis road	40 (4%)	10 (25%)	30 (75%)
	Parking lot	4 (<1%)	2 (50%)	2 (50%)
	Other	3 (<1%)	0 (0%)	3 (100%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Lighting condition	Daylight	685 (69%)	127 (19%)	558 (81%)
	Night	311 (31%)	74 (24%)	237 (76%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Curve type	Straight	879 (88%)	176 (20%)	703 (80%)
	Curve	117 (12%)	25 (21%)	92 (79%)

Variables	Categories	Total (column%)	Severity levels (row %)	
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Number of lanes	One lane	177 (18%)	35 (20%)	142 (80%)
	Two lanes	543 (54%)	119 (22%)	424 (78%)
	More than two lanes	248 (25%)	40 (16%)	208 (84%)
	Not specified	28 (3%)	7 (25%)	21 (75%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Road speed limit	Lower than 50 km/h	956 (96%)	178 (19%)	778 (81%)
	Higher than 50 km/h	30 (3%)	19 (63%)	11 (37%)
	None	10 (1%)	4 (40%)	6 (60%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**

Table 20: infrastructure characteristics and the percentage of severity levels EDPm accidents in France

4.2.6.1.4. Collision characteristics

Table 21 contains the two attributes utilized in the model regarding collision types and the percentage of accident severity levels. Specifically, two variables define collision types: side collisions and "other." Similarly, when a moving object is involved in the accident, the two variables are considered accidents with vehicles and "other" groups of other moving objects. Notice that there is no consideration for accidents involving fixed obstacles; the descriptive analysis has indicated the absence of valuable variables within the dataset.

Variables	Categories	Total (column%)	Severity levels (row %)	
			Serious & fatal	Minor
Collision type	Side	622 (62%)	111 (18%)	511 (82%)
	Other	374 (38%)	90 (24%)	284 (76%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**
Crash with moving obstacle	Vehicle	778 (78%)	147 (19%)	631 (81%)
	Other	218 (22%)	54 (25%)	164 (75%)
Total%		**996 (100%)**	**201 (20%)**	**795 (80%)**

Table 21: collision characteristics and the percentage of severity levels for EDPm accidents in France.

4.2.6.2. Process of building and validating the random forest model for e-scooter accidents in France using R programming

4.2.6.2.1. Modelling process

The mentioned variables in Table 19, Table 20, and Table 21 are used in building and validating the random forest model for EDPm accidents in France with severity levels as dependent variables using R programming. We split the data into training (70%) and testing (30%). Also, the cross-validation technique is used in the training set. The training set is divided into 10 equal folds, and in each iteration, one-fold is kept for testing, and the remaining is used for training the model.

As in the case of e-bike severity levels in France, the EDPm severity levels show an imbalance class issue, as previously noted, with (minor) accidents being more frequent than (serious & fatal). To overcome the issue related to class imbalance, we used the same technique as in the case of e-bike accidents in France, the Synthetic Minority Over-sampling Technique (SMOTE), to generate synthetic features from the less frequent class. In addition, to optimize the model performance, we used the tuning hyperparameters technique. Notice that one parameter that does not require tuning is the number of trees, as it is selected randomly. Throughout our experimentation, we tested different values and determined that the optimal value for this parameter was 150. For the other parameters, the following values have been assigned to each parameter (see Figure 67).

- Ntree = 150
- Mtry = 3
- Min_n = 40

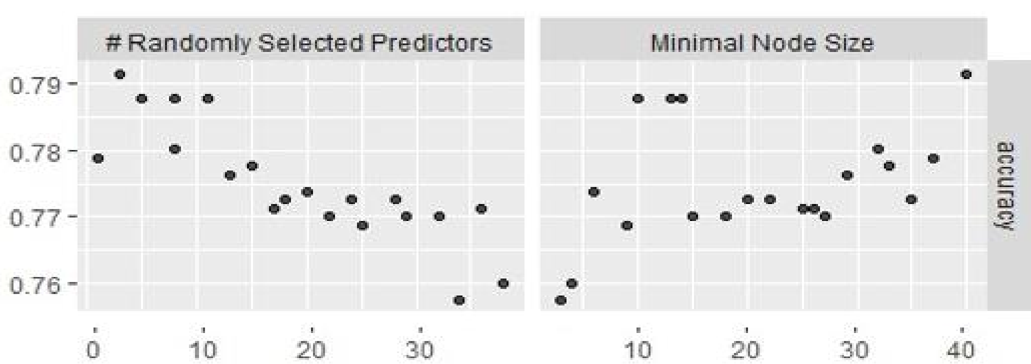

Figure 67: the model hyperparameters resulting from tuning for EDPm accidents in France.

The above hyperparameters are then used to train the random forest model; the model results are summarized in Table 22 (the confusion matrix). The model performs well in classifying minor accidents, with 525 correctly predicted as minor. Nevertheless, it shows limited capability in predicting serious and fatal accidents, with only 36 incidents correctly predicted and 31 misclassified. However, the issue of misclassifying serious and fatal accidents is merely due to the class imbalance. The dataset has only 20% of serious and fatal accidents. Additional reasons may be correlated to the quality of the data. As previously mentioned, the dataset contains accidents of personal travel devices and includes not only e-scooter accidents but also other types of personal motorized transport vehicles (EDPm). The difference in user characteristics and severity of accidents may lead to significant variability.

	Truth class		
predicted class		minor	serious & fatal
	Minor	525	104
	serious & fatal	31	36

Table 22: confusion matrix for trained random forest model for EDPm accidents in France.

4.2.6.2.2. Model validation

To validate the model on EDPm accidents data in France, we used 30% of the data as the testing set. The results of this testing set are presented in the confusion matrix (see Table 23).

	Truth class		
predicted class		minor	serious & fatal
	Minor	227	50
	serious & fatal	12	11

Table 23: confusion matrix for testing random forest model for EDPm accidents in France.

Due to imbalanced classes in the data, we apply equations (3), (4), and (5) to calculate the following performance measures: Precision, recall, and F1 -measure for both minor classes and serious and fatal classes. For minor classes, the precision represents the proportion of minor accidents correctly classified as minor out of all accidents predicted as minor, which in this case is 95%. The recall measures the model's ability to identify minor accidents, with a recall of 82%, indicating that the model captured 82% of all minor accidents. The F1 measure, the harmonic mean of precision and recall, balances these two performance measures and is 88% for minor accidents.

In contrast, the performance measures for serious and fatal accidents are significantly lower. The precision is 18%; however, the model aims to identify the variables affecting the severity levels resulting from EDPm accidents. Therefore, classifying minor accidents as serious and fatal will not undermine our objective. This lower precision can be accepted to some extent. Nevertheless, an issue should be raised with the recall equal to 48%, indicating that the model wrongly predicts nearly half of serious and fatal accidents. Consequently, the F1 measure for serious and fatal accidents is 26%, demonstrating the model's limited capability in this category.

4.3. Results

4.3.1. Variable importance for micro-mobility accidents for France and Belgium models

4.3.1.1. Variable importance for e-bike accidents for France and Belgium models

The variables affecting the outcome of e-bike accidents in France and Belgium are evaluated using the Gini index within the R programming environment. Table 24 reports the important variables resulting from the two models. However, the importance variables result shows significant variability due to the differences in the richness of the dataset in the two countries. The French dataset contains comprehensive information that led to more effective results in identifying the important variables.

In the French model, out of 47 variables used to build the random forest model, the model identifies 11 variables influencing the severity levels of e-bike accidents. It is worth mentioning that some of the identified variables, such as age reference category and urban areas, can be correlated to the usage patterns. The higher severe outcome resulting from e-bike accidents is correlated with the following variables: leisure trips without safety equipment, straight roads with two lanes, speed limits exceeding 50 km/h, and involvement of motor vehicles. In the case of the Belgian model, users who experienced accidents on cycle lanes marked on the ground and were involved with passenger cars were more likely to sustain injuries.

Factors influencing e-bike accidents	Variables (France)	Variables value (France)	Variables (Belgium)	Variables value (Belgium)
User characteristics	Age group	Reference category (from 14 years to 60 years old)	N/A	N/A
	Trip purpose	Leisure trips	N/A	N/A
		Home- work trips	N/A	N/A
	Use of safety equipment	No equipment	N/A	N/A
		Other	N/A	N/A
Infrastructure characteristics	Road speed limit	Higher than 50 km/h	N/A	N/A
	Curvature type	Straight	N/A	N/A
	Number of lanes	Two lanes	N/A	N/A
	Land use	Urban	N/A	N/A
	Accident location	On road lanes	Biker position	on cycle lanes marked on the ground
Collision characteristics	Moving objects	Motor vehicles	User type	Passenger car

Table 24: variables influencing the e-bike accident outcome in France and Belgium.

4.3.1.2. Variable importance for e-scooter accidents for France

The validation of the random forest model concerning e-scooter accidents in France revealed that the model had limited capability in correctly identifying the severe outcome by misclassifying nearly half of the accidents. The issue related to misclassification is linked to the huge class imbalance within the data as well as the data variability since the dataset represents personal motorized transport vehicles and not only e-scooters. However, it is worth identifying the variables influencing the severe outcomes of the accidents. Table 25 represents these variables.

Out of 47 variables used to build the model, the Gini index identifies 9 variables influencing the severity levels of the accidents. The variables contributing to severe outcomes in e-scooter accidents include leisure trips conducted without safety equipment, traveling on roads with two lanes, occurring outside of intersections, and involving side collisions.

Factors influencing e-scooter crashes	Variables	Variables value
User characteristics	Trip purpose	Leisure trip
	Use of safety equipment	No equipment
		Other
	Time range	Morning
		Evening
Infrastructure characteristics	Road type	Departmental road
	intersection	Outside intersection
	Number of lanes	Two lanes
Collision characteristics	Collision type	Side

Table 25: variables influencing the e-scooter accident outcome in France.

4.3.2. Comments on the results

The Random Forest models revealed several key factors related to user and trips, infrastructure, and collision characteristics that influence the severity levels of e-bike accidents in France, e-bike accidents in Belgium, and e-scooter accidents in France.

In the case of e-bike accidents in France and Belgium, the differences in the datasets highlight the importance of data richness in understanding the key risk factors that influence e-bike accident severity levels. The French dataset provides valuable inside users and trip, infrastructure, and collision characteristics, while the Belgian dataset lacks detailed disaggregated information regarding these factors. The nature of the French data allows us to investigate the severity levels more accurately by grouping the e-bike accidents into two different severity levels (serious & fatal) and (minor) accidents. This level of detail helps identify specific risk factors associated with more severe outcomes. In contrast, the nature of the Belgium dataset allows us to identify whether individuals involved in e-bike accidents sustained an injury or not.

Regarding e-bike accidents in France, the higher severe outcome resulting from e-bike accidents is associated with the following variables: leisure trips without safety equipment, straight roads with two lanes, speed limits exceeding 50 km/h, and involvement of motor vehicles. These findings underscore the importance of several key safety measures and highlight the importance of safety equipment such as helmets. In addition, avoiding e-bikes from using roads with high-speed limits (over 50 km/h) can significantly reduce e-bike accident severity.

In the case of e-bike accidents in Belgium, users who experienced accidents on cycle lanes marked on the ground and were involved with passenger cars were more likely to sustain injuries. The cycle lanes marked on the ground, as illustrated in Appendix B, might lead to significant interaction with other vehicular traffic, especially passenger cars.

Concerning e-scooter accidents in France, the dataset is consistent with e-bike data, as they both originate from the same source. The variables contributing to severe outcomes in e-scooter accidents include performing leisure trips without safety equipment, traveling on two-lane roads, having accidents outside of intersections, and experiencing side collisions.

In summary, the common factors that significantly influenced the severity levels of micromobility vehicles (e-bike and e-scooter) are the absence of safety equipment, accidents on two-lane roads, and accidents while performing leisure trips. These findings highlight the importance of safety equipment such as helmets. Additionally, they show the necessity of providing dedicated cycle lanes to improve the safe usage of micro-mobility. Finally, there is a need for technological advancement to reduce the interaction between micromobility vehicles and motor vehicles.

5. Technology advancement to improve the safety of micro-mobility vehicles

5.1. E-scooter and e-bike characteristics and safety

Figure 68: e-scooter and e-bike characteristics.
Source: G. Yannis, V. Petraki, R. Associate, and P. Crist,2024.

In terms of safety, the primary key difference between an e-scooter and an e-bike is related to the rider's position[95]. The standing position while riding an e-scooter exposes the rider to absorb the total impact of the fall [97]. Additional risk related to the stand position was observed while performing braking to move away from obstacles [95]. However, seated and standing positions improve the barking performance [95].

E-scooters are characterized by handlebars positioned on the top of the central column to provide stability and ensure safer steering with the foot platform [111]. Also, the e-scooter movement is like a bicycle movement [95]. Changing the fork-steerer column angle will change the characteristics of the front wheel and make the rider/vehicle's centre of mass similar to that of the bicycle [95]. In e-scooters, the forward-facing centre of mass has critical effects when e-scooters experience an accident with front obstacles. In such an accident, the rider's weight might be applied to the e-scooter handlebar, creating a facular effect that increases the likelihood of over-the-handlebar vaulting [97], [112], [113]. In addition, shifting the e-scooter centre of mass directly affects stability when riding at a lower speed; the backward and downward shifts for the e-scooter centre of mass enhance stability while the forward shifts decrease it [114].

Micromobility vehicles' wheel and tire sizes have a remarkable influence on safety [95]. These differences in the size of wheels and tires affect the vehicle's capability to absorb the impacts [95]. For instance, the large wheel size in an e-bike provides gyroscopic stability and is capable of absorbing impact more compared to the small wheel size of an e-scooter [95].

In addition, the small-sized wheels of e-scooters increase the possibility of riders experiencing falls, which has a direct effect on increasing head injuries [95]. Thus, larger e-scooter wheels provide more stable movement and decrease the possibility for riders to experience fall risk [95].

5.2. Technology advancement to improve the safety of e-bike and e-scooter based on the analysis and modelling for accidents in France and Belgium

The rapid increase in the use of e-bikes and e-scooters, both as shared vehicles and privately owned, highlights the importance of enhancing their safety to reduce the accident rate resulting from such vehicles. In this section, we will introduce several technological advancements based on the findings from the analysis and modelling we obtained in Chapter 4. The model results revealed several key risk factors that affect the severity of e-bike and e-scooter accidents. The following technologies are recommended for implementation by manufacturers and shared vehicle companies. It is worth mentioning that the technological advancements we proposed have been approved by experts within the enterprise that partnered with Politecnico di Torino to develop this thesis work.

5.2.1. Intelligent transport system (ITS): Vehicle to vehicle communications

The intelligent transport system (ITS) provides several technologies based on information and telecommunication systems [115]. Implementing the intelligent transport system aims to improve safety, improve traffic efficiency, and decrease environmental impacts [116]. Within the context of (ITS), vehicle-to-vehicle communication is comparative communication that uses the wireless network to exchange data and information between vehicles [115] within a range varying from a few meters to a few hundred meters [117]. The vehicle-to-vehicle communication protocol uses broadcast signals to send and receive messages [118]. Installing specific device in the vehicle allows messages to be quickly sent to the nearest vehicles [115]. shows different types of ITS communication including vehicle to vehicle communication, vehicle to infrastructure communication, and vehicle to pedestrian communication [115].

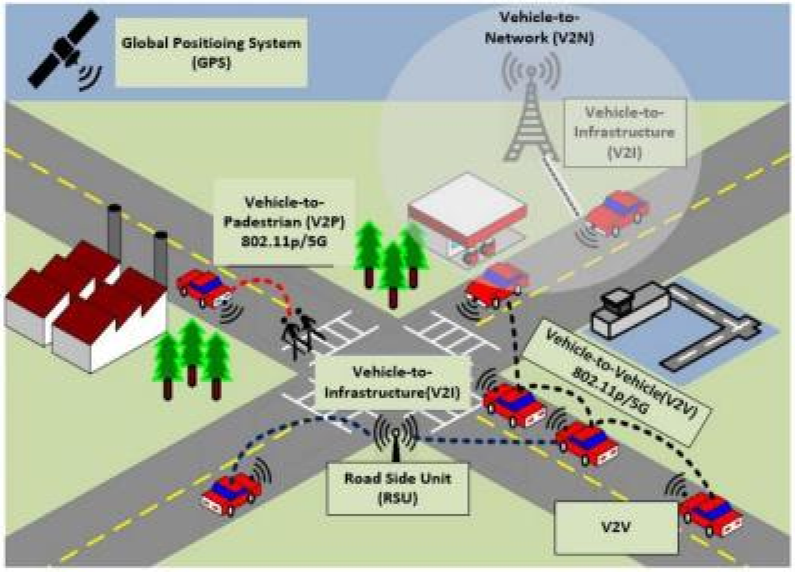

Figure 69: Situations involving vehicle-to-vehicle, vehicle-to-infrastructure communications, and vehicle-to-pedestrian within an ITS.
Source: Eze, Zhang, & Liu, 2014

The results from the modelling revealed that motor vehicle accidents are one of the critical risk factors in identifying the severity levels of e-bike accidents in France and Belgium; this can be correlated to the conflict in common shared spaces. Moreover, EDPm accidents involving motor vehicles were predominant, and side collisions were important in identifying the severity level resulting from EDPm accidents. Applying vehicle-to-vehicle communication can decrease conflict in the intersection (see Figure 70) by sending and receiving messages to the users. Also, it decreases the conflict between motor vehicles and micro-mobility vehicles where no cycle paths are available, as seen in (Figure 71).

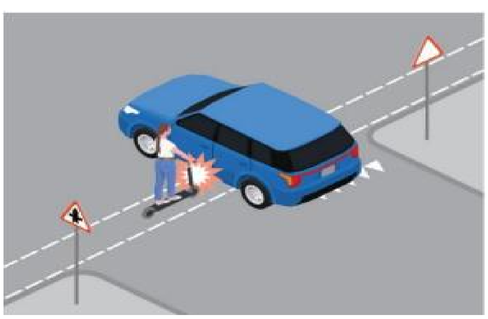

Figure 70: side collision between e-scooter and motor vehicle at the intersection.
Source: Nom de famille, P., & Nom de famille, P. (2023).

Figure 71: rear collision between e-scooter and motor vehicle in the road lane.
Source: Nom de famille, P., & Nom de famille, P. (2023).

5.2.2. Real time vehicle localization by integrating GPS and INS

In recent years, vehicle localization through satellite navigation systems like GPS (Global Positioning System) has been widely used in transport systems [119]. However, regarding individuals' safety, the GPS accuracy might not be sufficient due to signal interruption [119], which occurs in such cases as in tunnels or due to the effect of high buildings [119]. Therefore, integrating GPS with another localization system, such as the Inertial Navigation System (INS), provides reliable accuracy [119]. Inertial Navigation Systems (INS) are becoming increasingly popular in the industrial field due to their low cost; INS provides the vehicle's position, velocity, and attitude [119]. When integrating the two systems (GPS and INS), GPS provides absolute positioning, while INS offers high-rate updates [119].

The modelling result from e-bike accidents in France revealed that accidents occurred on roads with speed limits higher than 50 km/h, resulting in serious accidents. Also, it is worth noting that riding e-scooters on roads with such speed limit is allowed, but the road speed limit must not exceed 80 km/h, and there are specific requirements previously highlighted in Chapter 3. Due to the importance of such risk factors, we propose the application of real-time vehicle localization by integrating GPS and INS in e-bikes and e-scooters so that when the rider approaches roads at a speed higher than 50 km/h, the vehicle must alert to provide attention to the rider.

5.2.3. Smart safety equipment

The standing position on an e-scooter, the elevated head, and the higher distance from the ground increase the head acceleration during e-scooter accidents [95]. Also, e-scooter users experience almost double the number of head injuries compared to bicycle users [87]. It has been observed that helmets during e-scooter accidents decreased head trauma significantly [120]. However, using a helmet while riding an e-scooter is not mandatory in many European countries [29]. Despite the obvious safety benefits of wearing helmets, our analysis revealed that only 25% of e-scooter users who experienced an accident in France in 2022 were wearing helmets. However, the same year, the percentage of e-bike users wearing a helmet during an accident was almost double that of e-scooter users.

Furthermore, the implementation of law enforcement to obligate the use of helmets is showing little benefits, especially in shared e-scooters. For instance, although the non-use of helmets exposes users to financial penalties in Australia, helmet usage is still uncommon among e-scooter users [121]. Several factors can be correlated to such non-use of helmets, like lack of legislation support and knowledge about safe riding [121]. Another important reason is related to societal attitudes toward e-scooters. Users' perspectives towards e-scooters are often considered "harmless toys [122]."

Based on the previously mentioned factors, we propose that the use helmet must be compulsory across all European countries for e-bike and e-scooter users. We also propose using smart helmets, which are advanced technology supported by sensors that will allow the use of e-scooters and e-bikes only if the rider wears the smart helmet. Therefore, we propose that manufacturers and shared e-scooter companies provide smart helmets attached to e-scooters, as seen in (Figure 72).

Figure 72: Images showing helmets provided with shared e-scooters in Canberra, Australia
Source: Nathalie Ssi Yan Kai, Narelle Haworth, & Amy Schramm, 2024

Further suggestion is the application of smart vests; according to the previous analysis in Chapter 5 for e-bike and e-scooter accidents, the use of vests was observed in less than 2% of the users. Wearing a reflective vest during riding an e-scooter can significantly improve rider safety, increasing the visibility of other road users, especially at night and in bad weather conditions. Therefore, we propose the application of a smart vest by installing a small lighting source in the back of the vehicles which reflect on the back of the rider, as seen in (Figure 73).

Figure 73: smart reflective vest.

6. Conclusion

This Chapter aims to summarize the findings of this thesis in relation to the study's objectives. In addition, it provides recommendations based on the results of the analysis. Moreover, the limitation of this study is also demonstrated in this Chapter.

This study aims to perform a comprehensive analysis of the micro-mobility regulatory framework. Particularly for e-scooters and e-bikes in some European countries, including Belgium, France, Germany, and Italy. Also, the study aimed to investigate the usage and the accident patterns of such vehicles and related user characteristics. Furthermore, the safety concern toward micromobility vehicles is an essential aspect that needs to be considered. Therefore, we comprehensively analysed the accident distributions concerning user and trip, infrastructure, and collision characteristics. The analysis was based on e-bike and e-scooter accidents in France and on e-bike accidents in Belgium.

Additionally, to improve the safety usage of micromobility, we develop machine learning random forest models using R programming language. The models aimed to understand the important variables related to user and trip, infrastructure, and collision characteristics that influence the severity levels of the accidents. Finally, based on the result of the model, this study proposed several technological advancements that can be applied to improve safety usage.

Regarding e-scooter regulations, we found notable differences in the regulatory framework across the countries targeted by the study. The variability in the regulations might be associated with the recent establishment of these regulations. In most European countries where e-scooters are permitted to circulate, the regulations came into force between 2019 and 2020. In this study, which covered the usage patterns in Belgium, France, and Germany, we found that e-scooter users in these countries were predominantly males under 40 years old, and the most usage was observed in urban areas. In addition, male e-scooter users under 40 years old experienced the highest percentage of accidents. These findings are associated with the usage patterns previously mentioned.

Concerning e-bikes, we cover the regulatory framework in Belgium, France, and Germany, and we also investigate the usage and accident patterns related to user characteristics. Regarding the regulatory framework, we found that it is almost similar across the countries targeted by this study, which can be associated with the earlier introduction of e-bike regulations compared to e-scooters. The usage and accident patterns within the countries targeted in this study have shown some variability; at the same time, no gender differences were observed in Belgium when using e-bikes. However, the differences were notable in France and Germany. In Belgium and France, e-bikes were used more by individuals above 55 years old. In Germany, however, the usage of e-bikes is not significantly different among different age groups.

Regarding the accident patterns and victim characteristics, in Belgium, no gender variability in experiencing an accident was observed, while in France and Germany, males experienced more accidents. Both findings can be correlated to the usage patterns as previously mentioned. In addition, e-bike users in Belgium and France over 55 years have experienced the highest percentage of accidents.

The results from the random forest model for e-bike accidents in France revealed that the higher severe outcome is correlated with the following variables: leisure trips without safety equipment, straight roads with two lanes, road speed limits exceeding 50 km/h, and involvement of motor vehicles. For e-bike accidents in Belgium, users who experienced accidents on cycle lanes marked on the ground and were involved with passenger cars were more likely to sustain injuries.

Regarding e-scooter accidents in France, the results from the random forest model revealed the variables contributing to severe outcomes in e-scooter accidents include leisure trips conducted without safety equipment, traveling on roads with two lanes, occurring outside of intersections, and involving side collisions. Some of our findings were aligned with a previous study conducted by Almudena Sanjurjo-de-No et al., who utilized the random forest machine learning algorithm to build a model to analyse and predict injury severity in single micro-mobility accidents using 6030 single micro-mobility accidents in Spanish urban areas from 2016 to 2020. Almudena Sanjurjo-de-No et al. found that the severity levels of micromobility (bicycle, e-scooter, and other micro-mobility) accidents increase during leisure trips. Also, in general, they tend to sustain severe injuries when high speed is involved.

Based on the findings of our study, we proposed technological advancements to improve the safe usage of e-bikes and e-scooters. It is worth mentioning that the technological advancements we proposed have been approved by experts within the enterprise, which is interested in the entire thesis. We proposed the following technology to be implemented for both e-bike and e-scooter: vehicle-to-vehicle communication between users who share the same infrastructure, smart helmets, and smart reflective vests.

The limitation of this study is mainly related to the availability and richness of the data. Micromobility accident data across several European countries are scarce. Regarding the richness of the datasets, the random forest models did not consider the influence of important user characteristics that significantly influence e-bike and e-scooter accidents. Such as riding under the influence of alcohol and the effect of dual riding in an e-scooter. In addition, another important variable related to infrastructure characteristics that the models did not consider is the surface quality, such as defects, cracks, and discontinuities. Also, the e-scooter accident data in France did not distinguish e-scooters from other personal motorized transport vehicles (Engin de déplacement personnel motorisé [EDPm]). The difference in user characteristics and severity may lead to significant variability. This issue limits the model's ability to correctly predict severe accidents. Therefore, we recommend separating e-scooter accident data from other personal travel vehicles in the data-gathering process.

In conclusion, regardless of the previously mentioned limitations, the random forest models developed for e-bike accidents in France and Belgium are promising since they provide decent capability for correctly identifying the severity of the accidents. This help in recommending several technological advancements to improve the safe usage of micro-mobility.

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Appendix A – Regulatory framework for e-scooters and e-bike in some EU countries

Table 26: Regulatory framework for e-scooter in Belgium

Regulatory aspect	Description	Reference
Micro-mobility vehicle geometry and mass characterization	The maximum width of Motorized transport (e-scooter) vehicles is 1 meter; the Belgian regulations do not provide information about height, length, or mass.	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads 82bis.4
Rated continuous power	No information about continuous rated power is provided in the Belgian regulations.	N/A
Requirements for sound device Ringing bell "horn"	Motorized transport vehicles (e-scooter) with handlebars are equipped with an audible warning device that can be heard at 20 meters.	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads 82bis.2
Requirements for braking	Motorized transport vehicles (e-scooter) must be equipped with sufficiently effective brakes.	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads 82bis.3
Requirements for the lighting equipment	1- Motorized transport vehicles (e-scooter) are permanently equipped with a white reflector at the front and a red reflector at the rear.	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art. 82.1bis
	2- Motorized transport vehicles (e-scooter) are permanently equipped with side signage consisting of:	
	1°- either a white reflective strip on each side of the footrests;	
	2°- either a white reflective strip in the shape of a continuous circle on each side of the tire of the front wheel and the rear wheel or a combination of the two previous types.	
Use of infrastructure	1- When the public Road includes a cycle path, indicated by road markings as provided in Article 74 (see appendix B), users of motorized transport vehicles (e-scooter) are required to follow this cycle path.	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art9
	2- When the public road has a cycle path, indicated by signs D7 or D9 (see Appendix B), users of motorized transport vehicles (e-scooter) must follow it.	
	3- When part of the public road is indicated	

	by the D10 sign (see Appendix B), users of motorized transport vehicles (e-scooter) must use it	
	4- In the absence of a cycle path, riders can use the public road with speed limit of 50 km/h or less, but they must travel to the right with the direction of their travel and prioritize users who follow these parts of the public road; users of motorized transport vehicles (e-scooters) may use the level shoulders and parking lanes. Also, they can use the sidewalks and projecting shoulders outside built-up areas.	
	5- When signs F99b and F101b (see Appendix B) are used, users take the part of the path designated for them. They can, however, travel on the other part of the path provided, and they should give way to users who are there regularly.	
	6- in cycle zones, users of motorized transport vehicles (e-scooter) can use the entire width of the roadway when it is only open to their direction of traffic and half of the width located on the right side when it is open to both directions of traffic.	
General rules of riding	1- When users of motorized transport vehicles (e-scooter) must use the cycle path, they can leave it to change direction, overtake, or go around an obstacle.	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art2, Art9, Art12, Art22
	2- All users must give way to rail vehicles, and they must move away from the railway track as soon as possible.	
	3- All users must give way to those coming on their right, unless they are traveling in a roundabout or if the driver from the right is coming from a prohibited direction.	
	4- When cycling, wearing any device capable of emitting sound (headphones, earbuds or headphones) to your ear is prohibited. The use of a hand-held telephone is also prohibited.	
	5- It is prohibited to ride on public roads without holding the handlebars.	
Traffic bans ordered	1- riding on the sidewalk is prohibited unless you hold the e-scooter by your hand.	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art21
	2- Access to highways is prohibited.	

Max speed	25 Km/h	Traffic law "code de la route" MAY 15, 2022. — Law amending the royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads, regarding the regulation of transport vehicles Atr.2 number 1°
Helmet	Not mandatory	ETSC - National e-scooter rules in Europe
Insurance	Not mandatory	ETSC - National e-scooter rules in Europe
Carrying passengers	Not permitted	ETSC - National e-scooter rules in Europe
Drink-ride limit	Same as car	ETSC - National e-scooter rules in Europe
Minimum age	16 years old	Traffic law "code de la route" MAY 15, 2022. — Law amending the royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads, regarding the regulation of transport vehicles Atr.4 number 7°

Table 27: Regulatory framework for e-scooter in France

Regulatory aspect	Description	Reference
Micro-Mobility Vehicle Geometry and mass characterization	1- Total width shall not exceed 0.90 meters for motorized personal transport vehicles (e-scooter).	Traffic law " Code de la route" Decree No. 2019-1082 of October 23, 2019, relating to the regulation of personal transportation vehicles Art. 4, R. 312-10 number 7°
	2- The length shall not exceed 1.65 meters for Motorized personal transport vehicles (e-scooter).	Traffic law " Code de la route" Decree No. 2019-1082 of October 23, 2019, relating to the regulation of personal transportation vehicles Art. 5., R. 312-11 number 12°
	3- There is no information has been mentioned about the height in the regulations.	N/A
	4- Mass: The maximum weight for a motorized personal transport vehicle (e-scooter) is not indicated.	N/A
Rated continuous power	No information about continuous rated power	N/A
Requirements for sound device Ringing bell "horn"	1- All motorized personal transport vehicles (e-scooter) must be equipped with an audible warning device consisting of a bell whose sound can be heard at least 50 meters away.	Order of July 22, 2020, relating to the audible warning of motorized personal transport vehicles from OFFICIAL JOURNAL OF THE FRENCH REPUBLIC "JOURNAL OFFICIEL DE LA RÉPUBLIQUE FRANÇAISE"
	2- Audible warning devices comply with the provisions of the international standard ISO 14878: 2015.	
	3- Products legally marketed in another Member State of the European Union, or Turkey, or originating from an EFTA Member State, which is party to the EEA Agreement and legally put into circulation in that country, are presumed to be compatible with this measure. The application of this measure is subject to Regulation (EU) 2019/515.	
	4- The horn must be controlled by a device attached to the handlebars of the motorized personal transport vehicle (e-scooter).	
	5- An audible warning device complying with the provisions of this decree must be provided with the manufacturer's motorized personal transport vehicles (e-scooter). However, the installation of the device can be left to the owner of the e-scooter.	
	6- The audible warning devices supplied with the motorized personal transport vehicles (e-scooter) must be unambiguous and easily perceptible. The rider must be able to check the operation of the horn at any time.	

Requirements for braking	1- Motorized personal transport vehicles (e-scooter) must be designed and constructed in such a way as to allow their driver to operate the braking device with a hand or foot control while remaining in a normal driving position and with both hands on the steering control.	Order of July 21, 2020, relating to the braking of motorized personal transport vehicles from OFFICIAL JOURNAL OF THE FRENCH REPUBLIC "JOURNAL OFFICIEL DE LA RÉPUBLIQUE FRANÇAISE"
	2- During the tests described in Appendix C, the driver must not use his or her feet to control the machine except to activate the braking system, if applicable. The following situations should not occur a) Excessive jerking; b) Locking of the front wheel; c) Instability of the machine (for example, uncontrollable lifting of the rear wheel); d) Loss of control or balance of the driver; e) Excessive skidding. Note that, with some types of braking systems, it is not possible to completely avoid rear wheel skidding during braking; this is considered acceptable provided that the situations described in points (d) or (e) do not occur.	
	3- The hand-operated braking system or any of its components must not present any failure when subjected to the tests described in Appendix C.	
	4- When the brakes are subjected to the stopping tests the deceleration average total speed of the e-scooter must be greater than or equal to 1.7 m/s^2	
	5- In the event of failure of the electric braking, the machine must be able to brake normally or stop with a minimum deceleration of 1.25 (+/– 0.25) m/s^2.	
	6- The parking brake device must make it possible to keep the e-scooter stationary on an ascending or descending slope of 18%, even in the absence of the driver. The driver must be able to carry out this parking action from the driving position.	
Requirements for lighting and signalling equipment	1- The reflective devices provided for in Articles R. 313-18 to R. 313-20 of the Highway Code must conform to types approved under the conditions provided for in Article 31 of this decree. Adhesive retro-reflecting devices conforming to these approved types are permitted.	Traffic law " Code de la route" Title IV: Special provisions for cycles, motorized personal transport vehicles and mopeds (Articles 45 to 45 c)
	2- A white reflective device must be fixed vertically at the front and in the median longitudinal plane of motorized personal transport vehicles (e-scooter) to indicate the presence of the cycle or vehicle of motorized personal travel seen from the front.	
	3- The device can pivot according to the steering angle and be grouped with the front lantern.	
	4- By way of derogation, in the event of technical impossibility, multi-track personal transport vehicles may be equipped with a white reflective device at the front on each side of the median longitudinal plane of the vehicle.	

	5- The red reflective device must be fixed vertically to the rear of the motorized personal transport vehicles (e-scooter) between 0.35 and 0.90 meters. Distance from the ground between 0.05 meters and 0.50 meters and in such a way that it cannot be accidentally hidden by the clothing of the driver of the motorized personal transport vehicle (e-scooter).	
	6- Motorized personal transport vehicles (e-scooter) must have at least two orange catadioptric devices visible from the side on each side. One must be located in front of the transverse vertical plane passing through the rear extreme point of the front wheel; another must be located behind the transverse vertical plane passing through the front extreme point of the rear wheel. At least one of the devices on each side must be attached to a wheel so that no point on the illuminating surface is at a distance from the wheel axis less than two-thirds of the nominal radius of the wheel. The axis of each device must be perpendicular to the median longitudinal plane of the vehicle or to the plane of the wheel to which it is attached. Devices not attached to a wheel must be placed at a height above the self of between 0.35 meters and 1 meter so that they cannot be accidentally hidden by the rider's clothing or the driver of the motorized personal transport vehicles (e-scooter).	
	7- In the event of technical impossibility, motorized personal transport devices (e-scooter) are authorized to deviate from the criteria for positioning and fixing on the wheel provided for in these requirements. In this case, the catadioptric devices must be positioned on each side of the machine at a height above the ground between 0.05 meters and 0.50 meters to be visible.	
	8- The presence of the catadioptric devices provided for in the preceding paragraph (requirements) is, however, not obligatory on cycles, motorized personal transport vehicles, or mopeds whose tires are fitted with retroreflective devices conforming to a type approved by the Minister of Transport. In this case, the devices likely to cause superficial wear of the sidewall of a tire, such as, for example, the drive roller of the electric generator of the cycles, must be arranged so as not to be able to come into contact with the surfaces retroreflective.	

	9- The lantern or front position light, the rear red light, and the electric generator for cycles or motorized personal transport vehicles provided in Articles R. 313-4 and R. 313-5 of the Highway Code must conform to an approved type. The lamps fitted to these lights must also conform to an approved type.	
Use of infrastructure	1- In built-up areas, drivers of motorized personal transport vehicles (e-scooter) must travel on cycle lanes or paths. When the road is bordered on each side by a cycle path, they must take the one open to the right of the road, in the direction of traffic	Article R412-43-1 of Traffic law " Code de la route", Modified by Decree No. 2023-848 of August 31, 2023 - art. 1 Article R412-43-2 of Traffic law " Code de la route" Creation Decree n°2019-1082 of October 23, 2019 - art. 23
	In the absence of cycle lanes or paths, they can also circulate:	
	1° On roads where the maximum authorized speed is less than or equal to 50 km/h. Rider of motorized personal transport vehicles (e-scooter) must never drive head-on on the road.	
	2° On pedestrian areas under the conditions defined in the fourth paragraph of article R. 431-9.	
	3° On shoulders equipped with a road surface.	
	2- outside urban areas	
	1°- Outside urban areas, drivers of motorized personal transport vehicles (e-scooter) can travel on cycle paths or greenways, "greenway Zone independent of the road network and reserved for the circulation of non-motorized vehicles, pedestrians and horse riders	Article R412-43-1 of Traffic law " Code de la route", Modified by Decree No. 2023-848 of August 31, 2023 - art. 1
	2°- The traffic police authority may authorize driving on roads with a maximum permitted speed of 80 km/h. In this case, you will have to wear a helmet, dress in retro-reflective equipment and drive with the position lights on	
	3°-Parking on sidewalks is permitted, provided it does not obstruct pedestrians. However, the mayor can decide to prohibit it	
	3- By way of derogation from the provisions of 1 and 2, the authority vested with traffic police power may, by reasoned decision	
	1° Prohibit the circulation of machines on certain sections of the roads mentioned in 1 and 2, having regard to the needs of road safety and traffic, fluidity, and ease of passage.	
	2° Authorize the circulation of vehicles on the sidewalk, provided that they respect the walking pace and do not cause disruption to pedestrians.	
	3° Authorize traffic on roads with a maximum authorized speed of less than or equal to 80 km/h, provided that the state and profile of the roadway, as well as traffic conditions, permit it.	
General rules of riding	1- riders must wear retro-reflective equipment in case of traffic at night or insufficient visibility	Article R412-43-1 of Traffic law " Code de la route",

	during the day.	Modified by Decree No. 2023-848 of August 31, 2023 - art. 1
	2- If the provisions of 3° number 3 in Regulatory Aspect "use of infrastructure "are applied:	
	1° Any driver of a motorized personal transport vehicles (e-scooter) must:	
	A) Wear a helmet that complies with regulations relating to personal protective equipment, which must be attached.	
	B) Wear either a high visibility vest complying with regulations or retro-reflective equipment whose characteristics are set by order of the Minister responsible for road safety.	
	C) Carry on him/her a non-glaring and non-flashing additional lighting device whose characteristics are set by order of the Minister responsible for road safety.	
	D) Drive, day or night, with the position lights of your vehicle on.	
	2° A person aged at least eighteen who accompanies a driver of a motorized personal transport vehicles (e-scooter) under eighteen must ensure, when exercising legal or de facto authority over this or these drivers, that each is wearing a helmet under the conditions provided for 1° above.	
Traffic bans ordered	1- motorized personal transport vehicles (e-scooter) are prohibited from driving on the sidewalk. Otherwise, they must be held by hand.	Official website of Ministry of Ecological Transition and Territorial Cohesion "Ministère de la Transition écologique et de la Cohésion des territoires"
	2- Drivers of motorized personal transport vehicles (e-scooter) are prohibited from pushing or towing a load or vehicle.	Article R412-43-2 of Traffic law " Code de la route" Creation Decree n°2019-1082 of October 23, 2019 - art. 23
	3- Drivers of motorized personal transport vehicles (e-scooter) are prohibited from being towed by a vehicle.	
Max speed	25 km/h	Official website of Ministry of Ecological Transition and Territorial Cohesion "Ministère de la Transition écologique et de la Cohésion des territoires"
Helmet	Not mandatory	ETSC - National e-scooter rules in Europe
Insurance	E-scooter users must have civil liability insurance. This insurance covers damage caused to others (injury to a pedestrian, material damage to another vehicle, etc.). It is recommended to contact your insurer to, for example, adapt your home insurance contract or take out a specific insurance contract.	Official website of Ministry of Ecological Transition and Territorial Cohesion "Ministère de la Transition écologique et de la Cohésion des territoires"

Carrying passengers	Not permitted	Article R412-43-3 Traffic law " Code de la route" Modified by Decree No. 2023-848 of August 31, 2023 - art. 1
Drink-ride limit	Not allowed to ride under the influence of alcohol	Safer micro-mobility: Technical Background Report OECD/ITF 2024
Minimum age	14 years old	Article R412-43-3 of Traffic law " Code de la route", Modified by Decree No. 2023-848 of August 31, 2023 - art. 1

Table 28: Regulatory framework for e-scooter in Germany

Regulatory aspect	Description	Reference
Micro-Mobility Vehicle Geometry and mass characterization	1- a handlebar or support bar of at least 500 mm for small electric vehicles with a seat and of at least 700 mm for motor vehicles without a seat.	Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads"
	2- a total width of not more than 700 mm, a total height of not more than 1400 mm and a total length of not more than 2000 mm.	
	3- a maximum vehicle mass without driver of no more than 55 kg.	
Rated continuous power	1- not more than 500 watts, or of not more than 1400 watts if at least 60 percent of the power is used for self-balancing.	Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads" DIN EN 15194:2018-11 Nations Economic Commission for Europe (UNECE) Regulation (EU) No 107/2014 of the European Parliament and of the Council of 15 January 2014 ""Official Journal of the European Union (OJ L 323 of 7.11.2014, p. 52)
	2- The nominal continuous power is according to DIN EN 15194:2018-11	
	3- Uniform conditions for the approval of internal combustion engines or electric drive systems for the propulsion of motor vehicles of categories M and N regarding the measurement of the useful power and the maximum 30- to determine the minute power of electric drive systems	
Requirements for sound device Ringing bell “horn"	1- Small electric vehicles must be equipped with at least one sounding bell that meets the requirements of Section 64a of the Road Traffic Licensing Regulation stvzo	Straßenverkehrs-Zulassungs-Ordnung (StVZO) § 64a Einrichtungen für Schallzeichen Regulation No 28 of the United Nations Economic Commission for Europe (UN/ECE)
	2- Other audible signalling devices may also be installed d in compliance with Regulation No 28 of the United Nations Economic Commission for Europe (UN/ECE)	
	3- Small electric vehicles within the meaning of paragraphs 1 and 2 may only be used on public roads in accordance with the following regulations The standard “DIN EN 15194 Bicycles – Electrically assisted bikes – EPAC; German version EN 15194:2017” can be obtained from Beuth Verlag gmbh, Berlin.	(OJ L 323, dated 6.12.2011, p. 33) - Part II, Annex II of Commission Delegated Regulation (EU) No. 3/2014 of October 24, 2013) "Official Journal of the European Union"

Requirements for braking	1- must be equipped with two independent brakes 1°-be able to brake the vehicle to a standstill, 2°- act up to maximum speed.	1- eKFV Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads"
Requirements for braking	3°- Achieve at least a deceleration value of 3.5 m/s 2. 4°-if the other brake fails, a minimum deceleration of 44 percent of the braking effect according to number 3° can be achieved without the motor vehicle leaving its lane 2- A three- or four-wheeled small electric vehicle must be equipped with a permanently attached device that can detect the small electric vehicle	2- section 65 Paragraph 1 Sentence 1 of the Road Traffic Licensing Regulations (StVZO)
Requirements for lighting and signalling equipment	1- A small electric vehicle must be equipped with lighting equipment that meets the requirements of Section 67 paragraph 1 sentences 3 and 5, paragraph 2 sentences 2 to 7, paragraph 3, paragraph 4 sentences 1 and 4, paragraph 6 sentence 3 of the road traffic registration - Regulations and are of an officially approved design in accordance with Section 22a Paragraph 1 Number 22 of the Road Traffic Licensing Regulations, unless otherwise stipulated in the following provisions. The lighting equipment may be removable. Fluorescent materials and retro-reflective materials are also considered lighting equipment. Taillights and reflectors may be installed in one device. Tail lights may also have a brake light function for red light with a light intensity and light distribution of the brake light function in accordance with Regulation No No 50 of the United Nations Economic Commission for Europe (UNECE) – Uniform conditions for the approval of marker lamps, tail lamps, brake lamps, direction indicators and rear number plate lighting devices for vehicles of category L (OJ L OJ L 97, 29.3.2014, p. 1). 2- The lighting system can be supplied via a coupling to the energy storage for the drive 3- The side markings must have yellow reflectors acting on both sides in accordance with number 18 of the Technical Requirements for Vehicle Parts for Type Testing in accordance with Section 22a stvzo of July 5, 1973 (vkbl. P. 558), which was last published in the announcement of 23. February 1994 (vkbl. P. 233), or with ring-shaped retroreflective white stripes on the tires or rims of the front and rear wheels. For single-axle small electric vehicles, the marking of the external wheels is sufficient	eKFV Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads" & the Road Traffic Licensing Regulations (StVZO) Section 67, Section 22a, & the United Nations Economic Commission for Europe (UNECE) category L (OJ L OJ L 97, 29.3.2014, p. 1).

Requirements for lighting and signalling equipment	4- For small electric vehicles, it is permissible to equip them with forward and rear direction indicators in accordance with Section 67 Paragraph 5 Sentence 6 of the Road Traffic Licensing Regulations. Additionally 1°- The rear direction indicators may also swivel with the steering, 2°- The distance from the rearmost point of the vehicle to the direction indicators may be more than 300 mm, 3°- The maximum installation height of the front and rear direction indicators may be 1400 mm, 4°- The minimum installation height for rear direction indicators may be 150 mm if the vertical angle of geometric visibility is at least 25 degrees above the horizontal.	
Use of infrastructure	1- Within built-up areas 1°- small electric vehicles may only use structurally designed cycle paths, including shared footpaths and cycle paths. 2° - the traffic area of separate cycle paths and footpaths allocated to cycle traffic as well as cycle lanes. 3° - cycle streets. 4° - If these are not available, driving is permitted on roads or in traffic-calmed areas	Road Traffic Regulations (StVO) Appendix 2 sign 240, sign 241, sign 244.1, sign 325.1, sign 237 and sign 295
	2- Outside built-up areas 1° - small electric vehicles may only use structurally designed cycle paths. Including shared footpaths and cycle paths. 2° - the traffic area of separate cycle paths and footpaths allocated to cycle traffic. 3° - cycle lanes. 4° -cycle streets and road shoulder	
	5° - If these are not available, driving is permitted on road	
	3- For driving on other traffic areas. 1° - the road traffic authorities may, in deviation from paragraphs 1 and 2, allow exceptions for certain individual cases or generally for certain applicants. General approval of small electric vehicles on such traffic areas can be achieved by arranging the additional sign.	
General rules of riding	1- Anyone driving a small electric vehicle must drive one behind the other, must not attach themselves to moving vehicles and must not drive hands-free. 2- Small electric vehicles may not deviate from the requirement to drive as far to the right as possible on roads with multiple lanes.	eKFV Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads" & Road Traffic Regulations (StVO) sign 240 of Annex 2 to the Road Traffic Regulations

General rules of riding	3- If there are no direction indicators on a small electric vehicle, anyone driving a small electric vehicle must announce the change of direction in a timely and clear manner using hand signals so that other road users can adapt their behaviour accordingly.	
Traffic bans ordered	1- If there is a ban on all types of vehicles. 2- Is a ban on motor vehicles, a ban on motorcycles, a ban on motor vehicles, or a ban on small electric vehicles may only drive or enter there if this is permitted by the additional sign "small electric vehicles free" 3- If there is a ban on cycling.	eKFV Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads" & Road Traffic Regulations (StVO) Appendix 2, sign 250, sign 260, sign 254 and sign 267
Max speed	20 km/h	Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads"
Helmet	Not mandatory	ETSC - National e-scooter rules in Europe
Insurance	A valid insurance sticker for small electric vehicles.	Vehicle Registration Ordinance - FZV " Fahrzeug-Zulassungsverordnung" Section 56
Carrying passengers	Not permitted	ETSC - National e-scooter rules in Europe
Drink-ride limit	Same as car 0.5 and zero for under 21	ETSC - National e-scooter rules in Europe
Minimum age	14 years old	Elektrokleinstfahrzeuge-Verordnung - eKFV "Ordinance on the Use of Personal Light Electric Vehicles (PLEVs) on Public Roads"

Table 29: Regulatory framework for e-scooter in Italy

Regulatory aspect	Description	Reference
Micro-Mobility Vehicle Geometry and mass characterization	1- Length: 2 m 2- Width: 0,75 m at the widest point, including handlebar and turning indicators 3- Height: 1,5 m 4- The weight of the vehicle, empty, ready for the use, but without batteries, shall not overcome 40 kg 5- Scooters with mainly electric propulsion shall be equipped with tyres, with a minimum diameter of 203,2 mm (8")	Executive Decree of August 19th, 2022
Rated continuous power	Not exceeding 500 watts	ETSC - National e-scooter rules in Europe
Requirements for braking	Starting from 30 September 2022 scooters with mainly electric propulsion marketed in Italy shall be equipped with brake acting on both wheels	(Paragraph75-bis)
Requirements for lighting and signalling equipment	A- Lights and reflectors 1- Scooters with mainly electric propulsion shall be equipped with white or yellow front light and red fixed rear light. They shall also be equipped with red rear 2- yellows reflectors shall be applied on the side, and the front light shall be positioned not higher than 1,4 m from ground 3- stop lights are admitted, with following requirements: 1° red lights, with intensity not lower than 0,3 cd in a field 2° can be installed at a height between 0,15 m and 1,4 m from ground ±10° in the horizontal and vertical plane 3° other requirements are present in the Art. 224 of the so-called "Regolamento di attuazione al nuovo codice della strada" 4- all lights shall be power supplied. They can be supplied by a dedicated battery or by the battery suppling the electric motor. 5- The Executive Decree of August 19th, 2022, states also that the technical characteristics of the lights and reflectors are present in the Art.224 of the so-called "Regolamento di attuazione al nuovo codice della strada" B- Turn indicators	The Executive Decree of August 19th, 2022, Art.224, “Regolamento di attuazione al nuovo codice della strada"

Requirements for lighting and signalling equipment	The Executive Decree of August 19th, 2022, define technical characteristics of the turn indicators: 1- turn indicators shall be yellow 2- turn indicators shall be positioned at a high between 0,15 m and 1,4 m 1° two couples: positioned both in the front position and rear with respect to the driver and symmetrically to the longitudinal axis of the vehicle.	
	2° only a single couple of turn indicators is sufficient, in case they are visible from the front and from the rear	
	3- blinking shall occur at a frequency f = 1,5 ± 0,5 Hz, with pulse duration longer than 0,3 s. The measurement shall be performed at 95% of the maximum light intensity	
	4- other requirements are present in the Art. 124 of the so-called "Regolamento di attuazione al nuovo codice della strada", but with a variation in its paragraph 5: the light emitted shall not be lower than 0,3 cd	
	5- Alternatively, to what has been indicated by Executive Decree of August 19th, 2022, for points 2.2 and 2.3, the same decree states that it is accepted the conformity to the following regulations/standards	
	1° UNECE 6	
	2° UNECE 50	
	3° UNECE 148	
	5° ISO 6742-1:2015 (Cycles — Lighting and retro-reflective devices — Part 1: Lighting and light signalling devices)	
	4° ISO 6742-2:2015 (Cycles — Lighting and retro-reflective devices — Part 2: Retro-reflective devices)	
	5° UNI EN 17128:2020.	
Use of infrastructure	1- In inhabited areas	Paragraph 75-terdecies
	1° on roads with speed limit 50 km/h	
	2° in pedestrian areas	
	3° on pedestrian and cycle path	
	4° on all other type of cycle paths	
	2- out of inhabited areas	
	On cycle paths and in general on paths reserved to bicycle	
General rules of riding	For all the overnight period, and in case of poor visibility, scooters with mainly electric propulsion shall have front and rear lights switched on, and the driver shall wear a high visibility jacket or high visibility retroreflective shoulder strap	(Paragraphs 75-sexies and 75-septies), Paragraph 4-ter in Article 162 of Italian Traffic Law
Traffic bans ordered	1- On the sidewalks it is only allowed to drive the scooters by hand	Paragraph 75-undecies,

Traffic bans ordered	2- It is not allowed to park scooters on the sidewalks, except in the areas identified by the municipalities, whereas parking is allowed in the stalls reserved for cycles, mopeds and motor vehicles	(Paragraph 75-quinquiesdecies)
Max speed	20 Km/h	ETSC - National e-scooter rules in Europe
Helmet	Mandatory for users <18 years old	ETSC - National e-scooter rules in Europe
Carrying passengers	Not permitted	ETSC - National e-scooter rules in Europe
Drink-ride limit	Not specified	ETSC - National e-scooter rules in Europe
Minimum age	14 years old	ETSC - National e-scooter rules in Europe

Table 30: Regulatory framework for e-bike in Belgium

Regulatory Aspect	Description	Reference
Technical specifications	EN 15194: 2017 Standard	VIAS Institute
Rated continuous power	250 watts	Federal Public Service -Mobility and Transport
use of infrastructure	1- When the public road includes a cycle path, indicated by road markings as provided in Article 74 (see appendix B), e-bike users required to follow this cycle path	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art9, Art12, Art22
	2- When the public road has a cycle path, indicated by sign D7 or D9 (see appendix B), e-bike users required to follow this cycle path	
	3- When part of the public road is indicated by the D10 sign (see appendix B), e-bike users must use it	
	4- In the absence of a cycle path, riders can use the public road with speed limit of 50 km/h or less. But they must travel to the right in relation to the direction of their travel and give priority to users who follow these parts of the public road, e-bike users may use the level shoulders and parking lanes. also, they can use the sidewalks and projecting shoulders outside built-up areas	
	5- When signs F99b and F101b (see appendix B) are used, e-bike users take the part of the path designated for them. They can, however, travel on the other part of the path provided and they should give way to users who are there regularly.	
	6- in cycle zones, e-bike users can use the entire width of the roadway when it is only open to their direction of traffic and half of the width located on the right side when it is open to both directions of traffic	
General rules of riding	1- When users of e-bike are required to use the cycle path, they may leave it to change direction, to overtake or to go around an obstacle	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art2, Art9, Art12, Art22
	2- All users must give way to rail vehicles, and they must move away from the railway track as soon as possible.	
	3- All users must give way to those coming on their right, unless they are traveling in a roundabout or if the driver coming from the right is coming from a prohibited direction	
	3- When cycling, it is prohibited to wear any device capable of emitting sound (headphones, earbuds or headphones) to your ear. The use of a hand-held telephone is also prohibited	
	4- It is prohibited to ride on public roads without holding the handlebars.	
traffic bans ordered	1- riding on sidewalk is prohibited, however, users under the age of 10 years allowed to use sidewalks	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public

		roads Art21, Art 9
	2- access to highways is prohibited	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art21, Art 9
Max Speed	25 km/h	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads Art2
Helmet	not mandatory but highly recommended	Federal Public Service -Mobility and Transport
Insurance	not mandatory but highly recommended	Federal Public Service -Mobility and Transport
Carrying passenger	You can only transport a passenger if a seat is provided a child seat with two footrests, it is strongly recommended that the child wears a helmet	Traffic law "code de la route" Royal decree of December 1, 1975, relating to general regulations on the policing of road traffic and the use of public roads
Drink-ride limit	0.5‰	https://vias.be/storage/main/vs97-fr-web.pdf
Minimum age	no age restrictions	Federal Public Service -Mobility and Transport

Table 31: Regulatory framework for e-bike in France.

Regulatory aspect	Description	Reference
Technical specifications	EN 15194: 2017 Standard	Ministry of Economy, Finance, and Industrial and Digital Sovereignty
Rated continuous power	250 watts	Traffic law " Code de la route" Article R311-1, paragraph 6.10
Use of infrastructure	in urban areas, cyclists are obliged to use cycle lanes or paths.	Traffic law " Code de la route" Article R110-2
	in urban areas, In the absence of cycle paths or lanes, cyclists travel on roads where traffic speed is limited to 30 km/h	Traffic law " Code de la route" Article R412-28-1
	Cyclists can circulate in pedestrian areas at a walking pace and without disturbing pedestrians. They can travel on shoulders equipped with a road surface.	Traffic law " Code de la route" Art R 431-10
General rules of riding	outside urban areas, at night is mandatory to wear a retroreflective vest	Traffic law " Code de la route" Article R 431-1-1
	When cycling, it is prohibited to wear any device capable of emitting sound (headphones, earbuds or headphones) to your ear. The use of a hand-held telephone is also prohibited	Road Safety, Live Together website
Traffic bans ordered	Riding on sidewalks is prohibited, except for children under eight years old	Traffic law " Code de la route" article R 412-34
Max speed	25 km/h	Traffic law " Code de la route" Article R311-1, paragraph 6.10
Helmet	Wearing a helmet is compulsory for riders under the age of twelve years old	Decree No. 2016-1800 of December 21, 2016 & Traffic law " Code de la route"article R. 431-1-3).
Insurance	not mandatory but highly recommended	service-public.fr (the official website for French Administration)
Carrying passengers	Child transport is possible with a child set, it is mandatory for the child's safety to wear a properly fitted helmet	Road Safety, Live Together website
Drink-ride limit	0.5 g/l	Road Safety, Live Together website
Minimum age	no age restrictions	Traffic law " Code de la route"

Table 32: Regulatory framework for e-bike in Germany

Regulatory aspect	Description	Reference
Technical specifications	EN 15194: 2017 Standard	Gesetzliche Regulierung von Pedelecs (Legal regulation of Pedelecs)
Rated continuous power	250 watts	Road Traffic Act (StVG) § 1, paragraph 3
Use of infrastructure	obligation to use cycle paths	§2 paragraph 4 StVO
	Cyclists may also use right-hand shoulders if no cycle paths are present the use of sidewalk is not allowed	§2 paragraph 4 StVO
	Children up to the age of eight must, and children up to the age of ten may, use sidewalks with bicycles.	§2 paragraph 5, StVO
	If there is a structurally separated cycle path, children up to the age of eight may also use this cycle path, notwithstanding the first sentence. If a child up to the age of eight is accompanied by a suitable supervisor, this supervisor may also use the sidewalk with a bicycle for the duration of the supervision; a supervisor is considered suitable if they are at least 16 years old.	§2 paragraph 5, StVO
	Pedestrian traffic must not be endangered or obstructed. If necessary, the speed must be adjusted to pedestrian traffic.	§2 paragraph 5, StVO
General rules of riding	Cyclists may only listen to music at a volume that allows them to hear the traffic - regardless of whether they use on-ear headphones or in-ear headphones. For your own safety, it is of course best to avoid listening to music altogether while riding	The General German Automobile Club (Allgemeiner Deutscher Automobil-Club [ADAC])
Traffic bans ordered	the use of sidewalk is not allowed	§2 paragraph 5, StVO
	Pedestrian zones	The General German Automobile Club (Allgemeiner Deutscher Automobil-Club [ADAC])
	Motorways	The General German Automobile Club (Allgemeiner Deutscher Automobil-Club [ADAC])
Max speed	25 km/h	Road Traffic Act (StVG) § 1, paragraph 3
Helmet	no helmet obligation, however, is strongly recommended	The Federal Ministry for Digital and Transport
Insurance	not mandatory	The General German Automobile Club (Allgemeiner Deutscher Automobil-Club [ADAC])
Carrying passengers	Child bike seats are well suited for taking younger children on a bike. They are relatively inexpensive and easy to use. When buying, make sure they comply with DIN EN 14344.Children between the ages of one and seven can travel in a child seat, The child should also wear a helmet	The Federal Ministry for Digital and Transport

Drink-ride limit	1.6 ‰ (per mille)	The General German Automobile Club (Allgemeiner Deutscher
Minimum age	no minimum age restrictions	The General German Automobile Club (Allgemeiner Deutscher Automobil-Club [ADAC])

Appendix B – signages and road marking for cyclist in Belgium

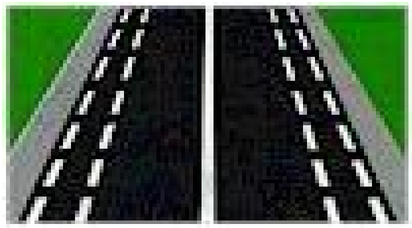

Figure 74: discontinuous lines of white colour indicate the present of cycle path Source: Belgium traffic law

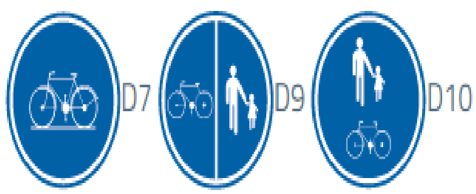

Figure 75: road signages indicate the present of (off road cycle path). Source: Belgium traffic law

Appendix C – Braking Test in France and Germany for electric scooter

1- E-scooter Braking Test according to French regulations

The braking test for e-scooters was published in (Annex 1) on July 21, 2020, relating to the braking of motorized personal transport vehicles (e-scooters) from the official journal of the French Republic. The test must be performed to guarantee certain criteria related to the following aspects:

Application of force

To active the braking system the maximum applied force must not be greater than 200 N measure it from 25 mm from the distal end of the hand control lever of the braking system.

Brake performance test conditions

The maximum total weight must be in accordance with the one indicated in the manufacturer's specifications; the surface on which the test should be performed must be dry concrete or asphalt with a maximum slope of 1%. Regarding weather conditions, the temperature should be between 5 to 35 degrees C, and the wind speed should not be greater than 3 m/s. Moreover, the driver must be in the position of a normal user, and he or she must maintain the same position throughout the test. The speed and the distance should be measured with an instrument with accuracy ± 1%.

Operating mode

The e-scooter should travel at a speed equivalent to 90% of the maximum speed, and then the brakes are applied for at least 3 seconds to attain constant deceleration. These procedures should be repeated ten times.

stopping performance

The calculation of (DCM) the average complete deceleration, décélération complète moyenne is necessary to assess the stopping performance, and the below equation must be implemented.

$$DCM = \frac{Vb^2 - Ve^2}{25.92 - (Se - Sb)}$$

Whereas,

DCM: the average complete declaration in m/s^2

Vb: the speed of the e-scooter, which is 80% from V1 in Km/h.

Ve: 10% from V1 in Km/h.

V1: is the speed at which the rider activates the brakes. It is in Km/h.

Sb: distance travelled between V1 and Vb.

Se: distance travelled between V1 and Ve.

Electric brake failure compensation test

The e-scooter must travel at maximum speed, and the battery power is cut off. Eventually, the scooter's deceleration is measured until it comes to a complete stop, excluding the final 0.5 seconds.

2- E-scooter Braking Test according to German regulations

The driving dynamics test should be performed to ensure and evaluate the company's knowledge on e-scooter safety measures and their ability to meet the standards set by German authorities. The objective of the test is to assess the e-scooter maximum design speed and the declaration. The test should be performed under the following conditions:

- The surface material must be concrete or asphalt
- The surface gradient must be greater than 1% but not higher than 3%.
- Ambient temperature must be between (0 to 45) degree C.
- E-scooter battery charge must be greater than 75%.
- E-scooter mass including, the driver, must not exceed 100 Kg.

a. Evaluating maximum design speed

To determine the maximum design speed, the vehicle to be tested must be driven over a distance of at least 50 meters at maximum power. The maximum speed reached must be determined. The test must then be repeated in the opposite direction. The maximum speed of the vehicle is expressed in km/h as an integer closest to the arithmetic mean of the speed values determined in two successive tests in both directions, which must not differ by more than 10%. If the arithmetic mean is exactly halfway between two integers, it is rounded up. The maximum speed determined in the tests must not deviate by more than 10% from the specified maximum design speed.

b. Deceleration

The vehicle must be driven straight on the test track at the maximum design speed. At a designated point, all braking devices must be applied as quickly as possible to the e-scooter must stop without risking a fall (e.g., due to a locking front wheel on single-track vehicles). If there is a risk of falling, the applied braking force must be reduced accordingly to keep the vehicle under control during braking. The stopping distance is measured in meters to two decimal places. The measurement must be repeated in at least five successive tests. The achieved average deceleration is calculated using the following formula. The deceleration of the vehicle is expressed in m/s^2 as a decimal number rounded to one decimal place.

$$a = \frac{V^2}{S}$$

Whereas,

a= Average deceleration [m/s2]

v = Output velocity [m/s]

s= stopping distance [m]

Appendix D – Attributes and their corresponding values for e-bike and e-scooter accidents data in France and Belgium

Table 33: attributes and their corresponding values for e-bike and e-scooter accidents data in France

Attribute abbreviations	Attribute definition	Attribute values
Num_acc	(accident number): identifier of the accident	Integer
Grav	Accident severity levels	Uninjured, fatality, hospitalized injury, slight injury
Sexe	Sex	Male, female
An_nais	Year of birth	Integer
Jour	Day	Integer
Mois	Month	Integer
An	Year	Integer
Trajet	Trip purpose	Not specified, not specified, home – work, home – school, purchase – shopping, leisure, other
Secu1	Presence and use of the safety equipment	Not specified, no equipment, helmet, reflective vest, gloves, not determinable, other
Agg	Accident location	Outside urban area, inside urban area
Intr	Intersection type	Outside intersection, x intersection, t intersection, y intersection, intersection with more than 4 branches, roundabout, square, level crossing, other intersection
Catr	Road category	Motorway, national road, departmental road, local road, off-public network, public-access parking area, urban muncipals roads, other
Lum	Lighting conditions	Daylight, dawn or dusk, night without public lighting, night with public lighting off, night with public lighting on
Plan	Plan layouts	Not specified, straight section, left curve, right curve, s-shaped
Nbv	Total number of traffic lanes	Integer

Vma	Maximum authorized speed at the location and at the time of the accident	Integer
Col	Collision type	Not specified, two vehicles - head-on, two vehicles - rear-end, two vehicles - side impact, three or more vehicles - chain collision, three or more vehicles - multiple collisions, other collision, no collision
Catv	Vehicle categories	E-bike, – EDPM (motorized personal travel vehicles)
Obs	Fixed obstacles struck	Not specified, not applicable, parked vehicle, tree, metal guardrail, concrete guardrail, other guardrail, building, wall, bridge pier, vertical signal support or emergency call post, pole, street furniture, parapet, island, refuge, high bollard, curb, ditch, embankment, rock face, other fixed obstacle on the roadway, other fixed obstacle on sidewalk or shoulder, roadway exit without obstacle, culvert - aqueduct head
Obsm	Moving obstacles struck	Not specified, none, pedestrian, vehicle, rail vehicle, domestic animal, wild animal, other

Table 34: attributes and their corresponding values for e-bike accidents data in Belgium

Attribute abbreviations	Attribute definition	Attribute values
key_download	(Accident Number): Identifier of the accident	Integer
TX_CLASS_VICT_EN	Accident severity levels	Uninjured, slightly injured, seriously injured, died within 30 days
TX_GENDER_EN	Gender	Man, woman, unknown
CD_AGE_CLS_DESCR_EN	Age group	0 to 4 years old, 5 to 9 years old, 10 to 14 years old, 15 to 19 years old, 20 to 24 years old, 25 to 29 years old, 30 to 34 years old, 35 to 39 years old, 40 to 44 years old, 45 to 49 years old, 50 to 54 years old, 55 to 59 years old, 60 to 64 years old, 65 to 69 years old, 70 to 74 years old, 75 to 79 years old, 80 to 84 years old, 85 and over, age unknown
DT_MONTH	Month	Integer
DT_YEAR	Year	Integer
TX_LOCAL_COND_EN	Aggregated information considering intersection types and infrastructure types	Roundabout, Roundabout, Roundabout, Tunnel, Unknown, Bridge, viaduct, Level crossing (railway), Building site/works affecting the roadway, Bridge, viaduct+Roundabout, Building site/works affecting the roadway + bridge, viaduct, None of the above
TX_POS_BIKER_EN	User position on the roadway and cycle path	Not applicable (not a moped rider/cyclist), None of the above, On a cycle lane marked on the ground, On or off the carriageway, Riding on cycle lane separated from carriageway, Riding on or leaving the suggested cycle lane, Unknown
TX_ROAD_USER_TYPE_EN	Vehicle involved in the accident	Different type of vehicle involved

TX_COLLISION_TYPE_EN	Collision types	Between 2 drivers: From the side (front/back/side), Between 2 drivers: Side against side, Between 2 drivers: Head-on collision, Between 2 drivers: Rear-end, With a pedestrian, Single user, no obstacle (incl. Fall), User against an obstacle located off the carriageway, User against an obstacle on the carriageway, Other or unknown, Type of collision not mentioned, Chain collision (3 or more drivers),Other or unknown
TX_CYCLING_TYPE_EN	Traffic flow direction	Not applicable, No cycle lane, One-way track, normal traffic flow, One-way lane, against the flow of traffic, Suggested cycle lane, normal traffic flow, Suggested cycle lane, against the flow of traffic, Bi-directional path, normal traffic flow, Bi-directional lane, against the flow of traffic, Unknown
TX_VICT_TYPE_EN	Victim types	Driver, passenger, other victims, unknown

Table 35: a comparative analysis of e-bike and e-scooter accidents data from Belgium and France.

Risk factor	Attribute definition	Belgian dataset	French dataset
User and trip characteristics	(Accident Number): Identifier of the accident	X	X
	Accident severity levels	X	X
	Gender	X	X
	Age	X	X
	Day	X	X
	Month	X	X
	Year	X	X
	Trip Purpose	X	
	Presence and use of the safety equipment	X	
Infrastructure characteristics	Accident location	X	
	Intersection type	X	X
	Road category	X	
	Lighting conditions	X	
	Plan layouts	X	
	Total number of traffic lanes	X	
	Maximum authorized speed at the location and at the time of the accident	X	
Collision characteristics	Vehicle categories	X	X
	Fixed obstacles struck	X	X
	Moving obstacles struck	X	X
	Victim type		X

Appendix E – R programming code for random forest models

1- Random forest model for e-bike accidents in France

```
# Installing packages and functions
library(readr)
library(tidyverse)
library(dplyr)
library(scales)
library(lubridate)
library(baguette)
library(doParallel)
library(foreach)
library(parsnip)
library(rsample)
library(recipes)
library(workflows)
library(themis)
library(FIT)
library(yardstick)
library(tidymodels)
library(randomForest)
library(eeptools)
library(pROC)
library(caret)
library(base)
library(hms)

# Reading e-bike accidents data file in France
ebike_France <- read.csv("D:/thesis/data/France_ebike/e-bike_France.csv")
glimpse(ebike_France)

# Data preprocessing
ebike_France$crash_time <- parse_time(ebike_France$crash_time, "%H:%M")
ebike_France
age_breaks <- c (-Inf,5, 20, 25, 30, 35,40, 45,50,55,60, Inf)
age_labels <- c ("5-10", "11-20", "21-25", "26-30", "31-35","36-40", "41-45","46-50", "51-55", "56-60", "60+")
ebike_France$age_group <- cut (ebike_France$age, breaks = age_breaks, labels = age_labels)
crash_ebike <- ebike_France %>%
na.omit() %>%
mutate (maximum_authorized_speed = case_when(
between((maximum_authorized_speed), -1, 0) ~ "none",
between((maximum_authorized_speed), 3, 50) ~ "max speed 50 km/h",
between((maximum_authorized_speed), 51, 110) ~ "max speed higher 50 km/h")) %>%
mutate (accident_date = ymd(paste(year, month, date, sep = "-"))) %>%
mutate (accident_date= wday(accident_date, label= TRUE)) %>%
mutate (time_range = case_when(
between(hour(crash_time), 6, 14) ~ "Morning",
between(hour(crash_time), 15, 23) ~ "Evening",
between(hour(crash_time), 0, 5) ~ "Night")) %>%
mutate (age_group = if_else (age_group%in% c("60+"),"+60","adult")) %>%
mutate (safety_equipment_1 = if_else (safety_equipment_1%in% c(-1),"not specified",
if_else (safety_equipment_1%in% c (0), "no equipment",
if_else (safety_equipment_1%in% c (2),"Helmet",
if_else(safety_equipment_1%in% c(4),"Reflective vest","other"))))) %>%
```

```
mutate (lanes_no = if_else(lanes_no%in% c(0),"not specified",
if_else (lanes_no%in% c (1), "one lane",
if_else (lanes_no%in% c (2), "two lanes","more than two lanes" )))) %>%
mutate (accident_location= if_else (accident_location %in% c(1), "on lane",
if_else (accident_location %in% c (5),"on cycle path","other"))) %>%
mutate (lighting_conditions=
if_else (lighting_conditions %in% c (1),"day","night")) %>%
mutate (curve_type=
if_else(curve_type %in% c (1),"stright","curve")) %>%
mutate (intersection=
if_else (intersection %in% c (1),"outside intersection",
if_else (intersection%in% c (3),"T intersection",
if_else (intersection%in% c (2),"X intersection",
if_else(intersection%in% c (6),"Roundabout","other"))))) %>%
mutate (moving_obstacle= if_else(moving_obstacle %in% c (2),"vech","other")) %>% mutate (collision_type=
if_else(collision_type %in% c (3),"side","other")) %>%
rename(injuries=grav) %>%
mutate (severity_levels= if_else(injuries %in% c(2,3), "serious", "minor")) %>% transmute(lighting_conditions,
severity_levels, location,   intersection,         collision_type,road_category, curve_type,age_group, sex, trip_purpose,
            safety_equipment_1, accident_location,time_range,
moving_obstacle,maximum_authorized_speed,  lanes_no ) %>%
mutate_if (is.integer, as_factor) %>%
na.omit()
glimpse(crash_ebike)
crash_ebike$severity_levels <- as.factor(crash_ebike$severity_levels)
crash_ebike$lighting_conditions <- as.factor(crash_ebike$lighting_conditions)
crash_ebike$time_range<- as.factor(crash_ebike$time_range)
crash_ebike$intersection <- as.factor(crash_ebike$intersection)
crash_ebike$collision_type <- as.factor(crash_ebike$collision_type)
crash_ebike$age<- as.factor(crash_ebike$age)
crash_ebike$road_category <- as.factor(crash_ebike$road_category)
crash_ebike$lanes_no <- as.factor(crash_ebike$lanes_no)
crash_ebike$trip_purpose <- as.factor(crash_ebike$trip_purpose)
crash_ebike$safety_equipment_1 <- as.factor(crash_ebike$safety_equipment_1)
crash_ebike$moving_obstacle <- as.factor(crash_ebike$moving_obstacle)
crash_ebike$maximum_authorized_speed <- as.factor(crash_ebike$maximum_authorized_speed)
crash_ebike$accident_location <- as.factor(crash_ebike$accident_location)
crash_ebike$ age_group   <- as.factor(crash_ebike$age_group )
crash_ebike$curve_type    <- as.factor(crash_ebike$curve_type )

# Data splitting
set.seed(2020)
crash_split <- initial_split(crash_ebike, prop = 0.8,  strata = severity_levels)
crash_train <- training(crash_split)
crash_test <- testing(crash_split)
set.seed(123)
crash_folds <-vfold_cv(crash_train, strata = severity_levels)
crash_folds

# Tuning to estimate the tuning hyperparameters
ranger_recipe <-
recipe (formula = severity_levels ~ ., data = crash_train) %>%
step_dummy (all_nominal(), -severity_levels) %>%
step_smote (severity_levels, neighbors = 10, over_ratio = 1)
ranger_spec <-
rand_forest (mtry = tune(), min_n = tune(), trees = 50) %>%
```

```
set_mode("classification") %>%
set_engine("ranger")
ranger_workflow <-
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(ranger_spec)
set.seed(7690)
doParallel::registerDoParallel()
ranger_tune <-
tune_grid(ranger_workflow, resamples =crash_folds, grid = 20)
show_best(ranger_tune, metric = "accuracy")
autoplot(ranger_tune)
final_rf <- ranger_workflow %>%
finalize_workflow(select_best(ranger_tune, metric = "accuracy"))
final_rf

# Building random forest
ranger_recipe <-
recipe(formula = severity_levels ~ ., data = crash_train) %>%
step_dummy(all_nominal(), -severity_levels) %>%
step_smote(severity_levels, neighbors = 10, over_ratio = 1)
ranger_spec <-
rand_forest(mtry =3, min_n = 37, trees = 50) %>%
set_mode("classification") %>%
set_engine("ranger")
ranger_workflow <-
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(ranger_spec)
ranger_workflow
set.seed(14228)
doParallel::registerDoParallel()
crash_res <- fit_resamples(
ranger_workflow,
crash_folds,
control = control_resamples(save_pred = TRUE))

# Evaluation on the traning
collect_metrics(crash_res)
# Evaluation on the testing
crash_fit <- last_fit(ranger_workflow, crash_split)
collect_metrics(crash_fit)

#confusion matrix training set
predictions <- collect_predictions(crash_res)
conf_mat<- predictions %>%
conf_mat(truth = severity_levels, estimate = .pred_class) #
print(conf_mat)
conf_mat %>%
autoplot(type = "heatmap")
predictions <- collect_predictions(crash_fit)

# Generate the confusion matrix
conf_mat <- predictions %>%
conf_mat(truth = severity_levels, estimate = .pred_class)
```

```
# Print the confusion matrix
print(conf_mat)
conf_mat %>%
autoplot(type = "heatmap")

# important variables
library(vip)
imp_spec <- ranger_spec %>%
set_engine("ranger", importance = "impurity")
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(imp_spec) %>%
fit(crash_train) %>%
pull_workflow_fit() %>%
vip(aesthetics = list(alpha = 0.8, fill = "midnightblue"))
```

2- Random forest model for e-bike accidents in Belgium

```
# Installing packages and functions
library(readr)
library(tidyverse)
library(dplyr)
library(scales)
library(lubridate)
library(baguette)
library(doParallel)
library(foreach)
library(parsnip)
library(rsample)
library(recipes)
library(workflows)
library(themis)
library(FIT)
library(yardstick)
library(tidymodels)
library(randomForest)
library(eeptools)
library(pROC)
library(caret)
library(base)
library(hms)

# Reading e-bike accidents data file in Belgium
ebike_Belg <- read.csv("D:/ thesis /Belgium/Data/e-bike_Belg.csv")

# Data preprocessing
crash <- ebike_Belg %>%
na.omit() %>%
mutate(severity_levels= if_else(severity_levels %in% c("uninjured"),"none", "injury")) %>%
mutate (age_group= if_else(age_group  %in% c("0 to 4 years old","5 to 9 years old",
"10 to 14 years old"),"0 to 14 years",
if_else(age_group %in% c("15 to 19 years old", "20 to 24 years old",
"25 to 29 years old", "30 to 34 years old",
"35 to 39 years old", "40 to 44 years old",
"45 to 49 years old" ), "15 to 49 years",
if_else(age_group %in% c ("50 to 54 years old", "55 to 59 years old",
"60 to 64 years old", "65 to 69 years old"),"50 to 69years","+70")))) %>%
transmute(severity_levels,weather_condition ,local_condition, road_user_type,
gender,age_group, victim_type, collision_type,biker_position,cycling_type) %>%
mutate_if(is.integer, as_factor) %>%
na.omit()
glimpse(crash)
crash$weather_condition <- as.factor(crash$weather_condition)
crash$severity_levels <- as.factor(crash$severity_levels)
crash$road_user_type  <- as.factor(crash$road_user_type )
crash$gender  <- as.factor(crash$gender )
crash$victim_type <- as.factor(crash$victim_type)
crash$collision_type <- as.factor(crash$collision_type)
crash$biker_position  <- as.factor(crash$biker_position )
crash$cycling_type  <- as.factor(crash$cycling_type )
crash$local_condition   <- as.factor(crash$local_condition  )
crash$age_group   <- as.factor(crash$age_group)
```

```
glimpse(crash)

#Data spilting
set.seed(2020)
crash_split <- initial_split(crash, strata = severity_levels)
crash_train <- training(crash_split)
crash_test <- testing(crash_split)
set.seed(123)
crash_folds <-vfold_cv(crash_train, strata = severity_levels)
crash_folds

# Tuning to estimate the tuning hyperparameters
ranger_recipe <-
recipe(formula = severity_levels ~ ., data = crash_train) %>%
step_other(local_condition, road_user_type,
victim_type, collision_type,biker_position,cycling_type)
ranger_spec <-
rand_forest(mtry = tune(), min_n = tune(), trees = 200) %>%
set_mode("classification") %>%
set_engine("ranger")
ranger_workflow <-
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(ranger_spec)
set.seed(7690)
doParallel::registerDoParallel()
ranger_tune <-
tune_grid(ranger_workflow, resamples =crash_folds, grid = 20)
show_best(ranger_tune, metric = "accuracy")
autoplot(ranger_tune)
final_rf <- ranger_workflow %>%
finalize_workflow(select_best(ranger_tune, metric = "accuracy"))
final_rf

# Building random forest
ranger_recipe <-
recipe(formula = severity_levels ~ ., data = crash_train)
ranger_spec <-
rand_forest(mtry = 4, min_n = 33, trees = 200) %>%
set_mode("classification") %>%
set_engine("ranger")
ranger_workflow <-
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(ranger_spec)
ranger_workflow
set.seed(14228)
doParallel::registerDoParallel()
crash_res <- fit_resamples(
ranger_workflow,
crash_folds,
control = control_resamples(save_pred = TRUE))

# Evaluation on the traning
collect_metrics(crash_res)
```

```
# Evaluation on the testing
crash_fit <- last_fit(ranger_workflow, crash_split)
collect_metrics(crash_fit)

#confusion matrix training set
predictions <- collect_predictions(crash_res)
conf_mat<- predictions %>%
conf_mat(truth = severity_levels, estimate = .pred_class)
print(conf_mat)
conf_mat %>%
autoplot(type = "heatmap")
predictions <- collect_predictions(crash_fit)

# Generate the confusion matrix
conf_mat <- predictions %>%
conf_mat(truth = severity_levels, estimate = .pred_class)

# Print the confusion matrix
print(conf_mat)
conf_mat %>%
autoplot(type = "heatmap")

# important variables
library(vip)
imp_spec <- ranger_spec %>%
set_engine("ranger", importance = "permutation")
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(imp_spec) %>%
fit(crash_train) %>%
pull_workflow_fit() %>%
vip(aesthetics = list(alpha = 0.8, fill = "midnightblue"))
```

3- Random forest model for e-scooter accidents in France

```
# Installing packages and functions
library(readr)
library(tidyverse)
library(dplyr)
library(scales)
library(lubridate)
library(baguette)
library(doParallel)
library(foreach)
library(parsnip)
library(rsample)
library(recipes)
library(workflows)
library(themis)
library(FIT)
library(yardstick)
library(tidymodels)
library(randomForest)
library(eeptools)
library(pROC)
library(caret)
library(base)
library(hms)

# Reading e-scooter accidents data file in France
escooter_France <- read.csv("D:/ thesis /Belgium/Data/e-scooter_Fra.csv ")
glimpse(escooter_France)

# Data preprocessing
escooter_France$crash_time <- parse_time(escooter_France$crash_time, "%H:%M")
escooter_France
age_breaks <- c( 0, 15, 30, 45, 60, Inf)
age_labels <- c("0-15", "16-30", "31-45", "46-60", "60+")
escooter_France$age_group <- cut(escooter_France$age, breaks = age_breaks,
labels = age_labels)
crash_escooter <- escooter_France %>%
na.omit() %>%
mutate(maximum_authorized_speed = case_when(
between((maximum_authorized_speed), -1, 0) ~ "none",
between((maximum_authorized_speed), 3, 50) ~ "max speed 50 km/h",
between((maximum_authorized_speed), 51, 110) ~ "max speed higher 50 km/h")) %>%
mutate(time_range = case_when(
between(hour(crash_time), 7, 15) ~ "Morning",
between(hour(crash_time), 16, 20) ~ "Evening",
between(hour(crash_time), 21, 23) ~ "Night",
between(hour(crash_time), 0, 6) ~ "af_mid_Night")) %>%
mutate(age_group = if_else(age_group%in% c("0-15"),"Reference","adult")) %>%
mutate(safety_equipment_1 = if_else(safety_equipment_1%in% c(-1),"not specified",
if_else(safety_equipment_1%in% c(0), "no equipment",
if_else(safety_equipment_1%in% c(2),"Helmet",
if_else(safety_equipment_1%in% c(4),"Reflective vest","other"))))) %>%
mutate(lanes_no = if_else(lanes_no%in% c(0),"not specified",
if_else(lanes_no%in% c(1), "one lane",
if_else(lanes_no%in% c(2), "two lanes","more than two lanes" )))) %>%
```

```
  mutate(accident_location= if_else(accident_location %in% c(1), "on lane",
if_else(accident_location %in% c (5),"on cycle path","other"))) %>%
mutate(lighting_conditions=
if_else(lighting_conditions %in% c (1),"day","night")) %>%
mutate(curve_type=
if_else(curve_type %in% c (1),"stright","curve")) %>%
mutate(intersection=
if_else(intersection %in% c (1),"outside intersection",
if_else(intersection%in% c (3),"T intersection",
if_else(intersection%in% c (2),"X intersection",
if_else(intersection%in% c (6),"Roundabout",
"other"))))) %>%
mutate(moving_obstacle= if_else(moving_obstacle %in% c (2),"vech","other")) %>%
mutate(collision_type= if_else(collision_type %in% c (3),"side","other")) %>%
rename(injuries=grav) %>%
mutate(severity_levels= if_else(injuries %in% c(2,3), "serious", "minor")) %>%
transmute(lighting_conditions, severity_levels,
location, intersection,        collision_type,road_category,
curve_type,age_group,
sex,       trip_purpose,      safety_equipment_1,
accident_location,time_range,
moving_obstacle,maximum_authorized_speed,  lanes_no ) %>%
mutate_if(is.integer, as_factor) %>%
na.omit()
glimpse(crash_escooter)
crash_escooter$severity_levels <- as.factor(crash_escooter$severity_levels)
crash_escooter$lighting_conditions <- as.factor(crash_escooter$lighting_conditions)
crash_escooter$time_range<- as.factor(crash_escooter$time_range)
crash_escooter$intersection <- as.factor(crash_escooter$intersection)
crash_escooter$collision_type <- as.factor(crash_escooter$collision_type)
crash_escooter$age<- as.factor(crash_escooter$age)
crash_escooter$road_category <- as.factor(crash_escooter$road_category)
crash_escooter$lanes_no <- as.factor(crash_escooter$lanes_no)
crash_escooter$trip_purpose <- as.factor(crash_escooter$trip_purpose)
crash_escooter$safety_equipment_1 <- as.factor(crash_escooter$safety_equipment_1)
crash_escooter$moving_obstacle <- as.factor(crash_escooter$moving_obstacle)
crash_escooter$maximum_authorized_speed <- as.factor(crash_escooter$maximum_authorized_speed)
crash_escooter$accident_location <- as.factor(crash_escooter$accident_location)
crash_escooter$curve_type  <- as.factor(crash_escooter$curve_type )
crash_escooter$ age_group   <- as.factor(crash_escooter$age_group )
glimpse(crash_escooter)

#Data spilting
set.seed(2020)
crash_split <- initial_split(crash_escooter, prop = 0.7,  strata = severity_levels)
crash_train <- training(crash_split)
crash_test <- testing(crash_split)
set.seed(123)
crash_folds <-vfold_cv(crash_train, strata = severity_levels)
crash_folds

# Tuning to estimate the tuning hyperparameters
ranger_recipe <-
recipe(formula = severity_levels ~ ., data = crash_train) %>%
step_dummy(all_nominal(), -severity_levels) %>%
step_smote(severity_levels, neighbors = 10, over_ratio = 1.25)
```

```
ranger_spec <-
rand_forest(mtry = tune(), min_n = tune(), trees = 150) %>%
set_mode("classification") %>%
set_engine("ranger")
ranger_workflow <-
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(ranger_spec)
set.seed(7690)
doParallel::registerDoParallel()
ranger_tune <-
tune_grid(ranger_workflow, resamples =crash_folds, grid = 20)
show_best(ranger_tune, metric = "accuracy")
autoplot(ranger_tune)

# Building random forest
ranger_recipe <-
recipe(formula = severity_levels ~ ., data = crash_train) %>%
step_dummy(all_nominal(), -severity_levels) %>%
step_smote(severity_levels, neighbors = 10, over_ratio = 1.25)
ranger_spec <-
rand_forest(mtry =3, min_n = 40, trees = 150) %>%
set_mode("classification") %>%
set_engine("ranger")
ranger_workflow <-
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(ranger_spec)
ranger_workflow
set.seed(14228)
doParallel::registerDoParallel()
crash_res <- fit_resamples(
ranger_workflow,
crash_folds,
control = control_resamples(save_pred = TRUE))

# Evaluation on the traning
collect_metrics(crash_res)

# Evaluation on the testing
crash_fit <- last_fit(ranger_workflow, crash_split)
collect_metrics(crash_fit)

#confusion matrix training set
predictions <- collect_predictions(crash_res)
conf_mat<- predictions %>%
conf_mat(truth = severity_levels, estimate = .pred_class)
print(conf_mat)
conf_mat %>%
autoplot(type = "heatmap")
predictions <- collect_predictions(crash_fit)

# Generate the confusion matrix
conf_mat <- predictions %>%
conf_mat(truth = severity_levels, estimate = .pred_class)
```

```
# Print the confusion matrix
print(conf_mat)
conf_mat %>%
autoplot(type = "heatmap")

# important variables
library(vip)
imp_spec <- ranger_spec %>%
set_engine("ranger", importance = "permutation")
workflow() %>%
add_recipe(ranger_recipe) %>%
add_model(imp_spec) %>%
fit(crash_train) %>%
pull_workflow_fit() %>%
vip(aesthetics = list(alpha = 0.8, fill = "midnightblue"))
```