European Commission

Thematic Report

Powered Two-Wheelers

Mobility and Transport

This document is part of a series of 20 thematic reports on road safety. The purpose is to give road safety practitioners and the general public an overview of the most important research questions and results on the topic in question. The level of detail is intermediate, with more detailed papers or reports suggested for further reading. Each report has a 1-page summary.

Contract:	This document has been prepared in the framework of the EC Service Contract MOVE/C2/SER/2022-55/SI2.888215 with National Technical University of Athens (NTUA), SWOV Institute for Road Safety Research and Kuratorium für Verkehrssicherheit (KFV).
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Referencing:	Reproduction of this document is allowed with due acknowledgement. Please refer to the document as follows: *European Commission (2024). Road safety thematic report – Powered Two-Wheelers. European Road Safety Observatory. Brussels, European Commission, Directorate General for Transport*.

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Contents

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Summary

Powered Two-Wheelers (PTWs), which encompass both mopeds and motorcycles, play a crucial role in traffic across European countries. They are primarily used for leisure, commuting, and long-distance travel. However, they present significant road safety challenges.

PTWs are about 20 times riskier compared to cars, with mopeds having a higher crash rate than motorcycles. Despite advancements like ABS becoming mandatory in 2013 for motorcycles, PTW fatalities still constitute a significant portion of road deaths in the EU. Although the absolute number of PTW rider fatalities decreased over the last decade, the share of total fatalities slightly increased, highlighting their persistent vulnerability to road risks. Crash characteristics show that male PTW riders, especially young males, are at higher risk, with a significant number of fatalities among those aged 15-19 for mopeds and 25-29 for motorcycles. Motorcycle rider fatalities are more frequent during weekends, reflecting different usage patterns. Single-vehicle crashes are common among PTWs, especially motorcycles.

Helmet use among PTW riders is generally high, but countries like Greece and Cyprus show lower compliance. Helmet use varies by road type, with lower usage on urban roads in some countries.

The primary causation factors for PTW crashes include visibility issues, with PTW riders often overlooked by other road users. Speed, young age, lack of experience, and risky behaviours such as speeding and disobeying traffic rules also contribute to crashes. Vehicle-related factors like design, braking difficulties, and loss of control linked to road conditions further exacerbate risks. Road environment plays a critical role in PTW rider safety. Poor road surfaces, water, oil, obstacles, and inadequate road markings can lead to severe crashes. Infrastructure, such as crash barriers, often does not take PTW riders into account, increasing the severity of crashes when collisions occur.

Countermeasures should adopt a safe system approach, focusing on improving infrastructure, enhancing vehicle safety, setting appropriate speeds, promoting safer behaviour while fostering the harmony of interactions between different types of road users, and ensuring adequate enforcement.

1. What is the problem?

1.1 What are Powered Two-Wheelers?

Powered Two-Wheelers (PTWs), which encompass both mopeds and motorcycles, play a crucial role in traffic across European countries. With their two wheels in line, slim bodywork, and favourable power-to-weight ratio, PTWs are an economical and attractive means of transport that can offer a specific sense of pleasure. They can be used for transporting goods and people, as in the case of low and middle-income countries, or as a suitable means of transportation in congested traffic (Slootmans et al., 2017; Nikolaou et al., 2024).

1.1.1 Mopeds

Mopeds are defined in the Driving Licence Directive 2006/126/EC (European Union, 2006) as: "Two-wheel vehicles or three-wheel vehicles with a maximum design speed of not more than 45 km/h, as defined in Article 1(2)(a) of Directive 2002/24/EC of the European Parliament and of the Council of 18 March 2002 relating to the type-approval of two or three-wheel motor vehicles (1) (excluding those with a maximum design speed under or equal to 25 km/h), and light quadricycles as defined in Article 1(3)(a) of Directive 2002/24/EC". This category also includes, among others, speed pedelecs and light mopeds (maximum speed of 25 km/h).

A category AM driving licence is required to ride a moped, scooter or light motor-powered vehicle with a maximum engine capacity of 50 cc or a maximum rated power equal to or less than 4 kW (electric motors) and whose maximum speed does not exceed 45 km/h (some exceptions apply). This can be obtained after passing a theoretical test, which is sometimes accompanied by a practical training course and exam. The minimum age for this category is fixed at 16 years (European Commission, 2018).

Speed pedelecs, fast electric bicycles (with obligatory type approval according to EN168/2013) offering pedal support up to a speed of 45 km/h, are a recent innovation. They have been classified as a "moped" by the European Union (European Union, 2013). Even though they look like a bicycle and riders have to pedal to move, they have to act under the traffic rules for mopeds (Vlakveld et al., 2021).

Mopeds offer a flexible way to get around and are a convenient, affordable, and environmentally friendly mode of transport. In urban areas, they have the potential to travel relatively quickly, while in rural areas they offer mobility options for users who do not have access to a car or other means of transport. Because mopeds are an individual transport mode, they offer a sense of freedom in personal mobility and flexibility. They are a sustainable urban mode of mobility with a minimum footprint in terms of riding and parking space requirements (OECD/ITF, 2015).

However, the high vulnerability of moped riders in traffic is the downside of this "light" way of moving. Together with pedestrians, cyclists and motorcycles, moped riders are part of the group of “vulnerable road users” (European Union, 2020). Moreover, mopeds are one of the only types of motorised transport available to 16-year-olds, which is why they are popular with young road users. This young age of moped riders, together with the lack of sufficient training and experience with motorised vehicles, means there is a risk that riders lack basic driving skills and are sometimes not able to assess adequately traffic situations and the dangers linked to riding a PTW (Ceunynck et al., 2018).

1.1.2 Motorcycles

Motorcycles distinguish themselves from other means of transport by their diversity: their dimension, motorisation, riding position, the environment in which they are ridden (urban, rural, off-road, etc.), the riders’ motivation (commuting, leisure, thrill-seeking, etc.) and their specific movement in traffic (use of lanes, lane filtering, position in curves, etc.) (Delhaye & Vandael Schreurs, 2022).

Furthermore, motorcycles vary dramatically in design with respect to size, weight and performance capacity. Riders can select a certain type of motorcycle based on their riding practices. Examples of types of motorcycles are standard motorcycles, dual-purpose motorcycles (i.e. adventure), touring motorcycles, cruisers, choppers, sport, sport touring, supersport, off-road motorcycles, all-terrain motorcycles, etc. (Teoh & Campbell, 2010). The best-selling motorcycle type (over 125cc engine size) in Europe has for several years been the adventure motorcycle, a type of motorcycle designed for long-distance touring and capable of handling a variety of terrains, including both on-road and off-road conditions.

The enormous vulnerability of motorcyclists in traffic is the downside of this flexible and agile way of getting around. Motorcycle riders are still relatively unprotected, even when they wear personal protective equipment such as helmets, protective suits, boots and gloves. Motorcycles have only two wheels, which makes them a self-balancing vehicle. At the same time, a motorcycle moves as fast as a car but has the added capability of accelerating more rapidly, which can surprise other road users and increase the overall risk (Slootmans et al., 2017).

Motorcycles are defined as “two-wheel or three-wheel vehicles with or without a sidecar” in the Driving Licence Directive 2006/126/EC (European Union, 2006). Motor tricycles (a.k.a. trikes), which are vehicles with three symmetrically arranged wheels, are also included in the category of motorcycles. Three sub-categories of motorcycle driving licences can be distinguished (Table 1):

Table 1*. Motorcycle categories according to the Driving Licence Directive 2006/126/EC*

Licence	Motorcycle restrictions	Early access (A1@16y)	Late access (A1@18y)
A1	Engine capacity: max 125cc Motor capacity: max 11kW Specific capacity: max 0.1kW/kg	16 years	18 years
A2	Motor capacity: max 35kW Unthrottled capacity: max 70kW Specific capacity: max 0.2kW/kg	18 years	20 years
A	No restrictions	Progressive access: 20 years Direct access: 24 years	Progressive access: 20 years Direct access: 24 years

1.2 How PTWs participate in traffic

Table 2 presents the latest available data on the fleet of PTWs across the EU countries, derived from EUROSTAT. These data, referring to the year 2022, encompass both mopeds and motorcycles, which play a significant role in personal transportation across the EU. The data include the number of PTWs, national populations, and the number of PTWs per thousand inhabitants, offering a comprehensive overview of PTW prevalence and distribution within the EU.

The following analyses highlight the diversity in PTW usage across different EU Member States, providing insights into transportation trends. Overall, the data illustrate that PTWs are most common in southern European countries (Vanpée et al., 2022). Specifically, Greece has the highest number of PTWs per thousand population (306.9) indicating a high reliance on PTWs for transportation. Italy follows with 174.5 PTWs per thousand population, showing a significant preference for PTWs among Italians. On the contrary, the lowest rates are observed in Ireland and Romania with 9.3 and 10.1 PTWs per thousand population, respectively, indicating that PTWs are not a primary mode of transportation in these countries.

Table 2*. Number of mopeds and motorcycles by EU country, 2022 (Source: EUROSTAT)*

	Mopeds 2022	Motorcycles 2022	PTWs 2022	Population 2022	PTWs/ thousand population
Belgium	288,428	515,215	803,643	11,617,623	69.2
Bulgaria	89,656	136,919	226,575	6,482,484	35.0
Czechia	483,102	1,266,945	1,750,047	10,516,707	166.4
Denmark	27,182	169,237	196,419	5,873,420	33.4
Germany	475,281	4,757,613	5,232,894	83,237,124	62.9
Estonia	21,070	46,095	67,165	1,331,796	50.4
Ireland	1,820	45,430	47,250	5,060,004	9.3
Greece	1,486,169	1,724,438	3,210,607	10,459,782	306.9
Spain	1,765,188	4,061,665	5,826,853	47,432,893	122.8
France	n/a	n/a	n/a	67,957,053	n/a
Croatia	75,421	92,597	168,018	3,862,305	43.5
Italy	3,000,000	7,302,597	10,302,597	59,030,133	174.5
Cyprus	9,774	32,112	41,886	904,705	46.3
Latvia	37,550	35,732	73,282	1,875,757	39.1
Lithuania	18,686	59,984	78,670	2,805,998	28.0
Luxembourg	8,689	26,474	35,163	645,397	54.5
Hungary	n/a	210,746	n/a	9,689,010	n/a
Malta	2,810	37,874	40,684	520,971	78.1
Netherlands	1,222,944	690,724	1,913,668	17,590,672	108.8
Austria	277,340	652,485	929,825	8,978,929	103.6
Poland	1,438,681	1,830,963	3,269,644	36,889,761	88.6
Portugal	n/a	n/a	n/a	10,352,042	n/a
Romania	6,699	185,038	191,737	19,042,455	10.1
Slovenia	72,287	81,172	153,459	2,107,180	72.8
Slovakia	31,246	139,157	170,403	5,434,712	31.4
Finland	361,243	290,233	651,476	5,548,241	117.4
Sweden	104,136	313,889	418,025	10,452,326	40.0
EU25	11,305,402	24,705,334	36,010,736	367,390,385	98.0

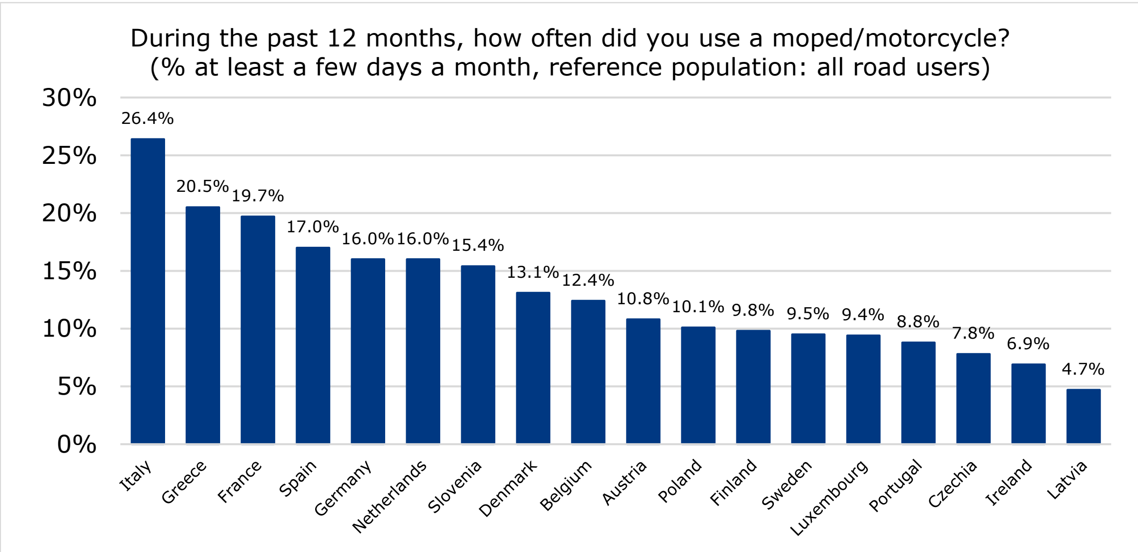
The ideal metric to investigate how PTWs participate in traffic would be exposure indicators such as passenger-kilometers or vehicle-kilometers travelled. However, such detailed data for EU countries are rare and quite limited, making it challenging to fully assess the impact and usage patterns of PTWs in traffic. Despite these limitations, some data on billion kilometers ridden by PTW users are available for a subset of EU countries over the period 2018-2021 (Carson et al., 2023).

***Table 3**. Billion km ridden by PTW users over the period 2018-2021 (Source: Carson et al., 2023)*

	2018	2019	2020	2021
Austria	1.726	1.759	1.812	n/a
Estonia	0.056	0.058	0.056	0.061
France	11.340	11.340	9.583	9.822
Croatia	0.304	0.306	0.287	0.282
Ireland	0.109	0.114	0.101	n/a
Latvia	0.061	0.057	0.066	0.064
Netherlands	1.462	1.283	0.945	0.894
Sweden	0.645	0.662	0.692	0.653
Slovenia	0.169	0.175	0.202	0.214

Another way to explore how PTWs participate in traffic is through surveys and questionnaires, which can provide valuable insights into PTW riders' behaviour, travel patterns, and the frequency of PTW use. These surveys can help fill the gaps left by the absence of comprehensive exposure data, offering a qualitative perspective on PTW usage across countries. As observed in the following Figure, based on the results of the latest edition of the E-Survey of Road Users' Attitudes (ESRA) survey in 2023, the proportion of respondents who ride a moped or a motorcycle at least a few days a month is highest in Italy and Greece, and lowest in Ireland and Latvia (Vias institute, 2024).

***Figure 1**. Percentage of respondents claiming to ride a moped/ motorcycle at least a few days a month (Source: Vias institute, 2024).*



The RIDERSCAN project showed that almost half of all respondents claim to use a PTW primarily for leisure. One third of the respondents use their PTW mainly for commuting, while almost two out of 10 respondents use their vehicle for long distance travelling (Delhaye & Marot, 2016).

2. PTWs and road safety

2.1 Crash risk

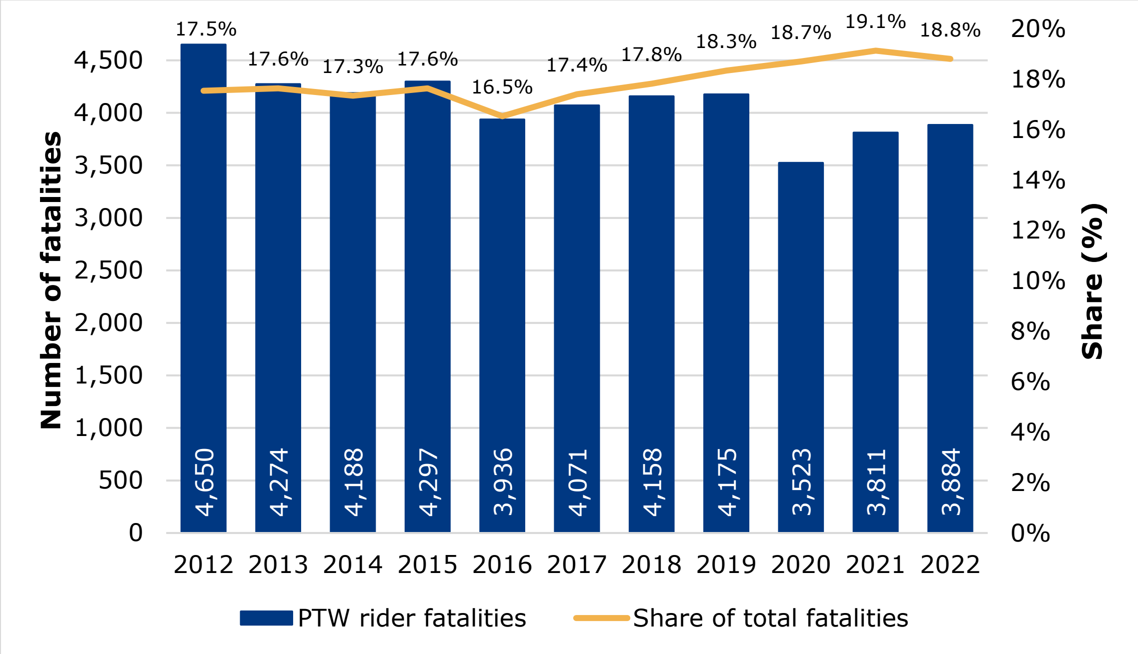
Exposure data can be used in order to determine risks in more detail. The number of kilometers travelled by PTWs gives a good proxy of their exposure to risk. Other indicators to measure exposure, such as total travel time, are not collected on a regular basis. It is therefore difficult to determine crash risk (OECD/ITF, 2015). The OECD estimates that PTWs in general are about 20 times riskier compared to cars (OECD/ITF, 2015). Findings from Australia indicate that the crash rate of a moped in terms of distance travelled could be up to four times greater compared to the crash rate of a motorcycle." (Blackman & Hayworth, 2013).

Especially for motorcycles, there is a significant difference in safety features before and after 2015. For example, ABS became mandatory in the EU in 2013 through Regulation (EU) No 168/2013. This regulation required all motorcycles in the L3e-A1 subcategory to be equipped with an advanced braking system, which could be ABS, a combined braking system (CBS), or both, at the manufacturer's discretion. Given the implementation of these enhanced safety features, an update on the crash risk for motorcycles would be appropriate to assess the impact of these regulations on crash rates and rider safety.

2.2 General trend in the number of fatalities

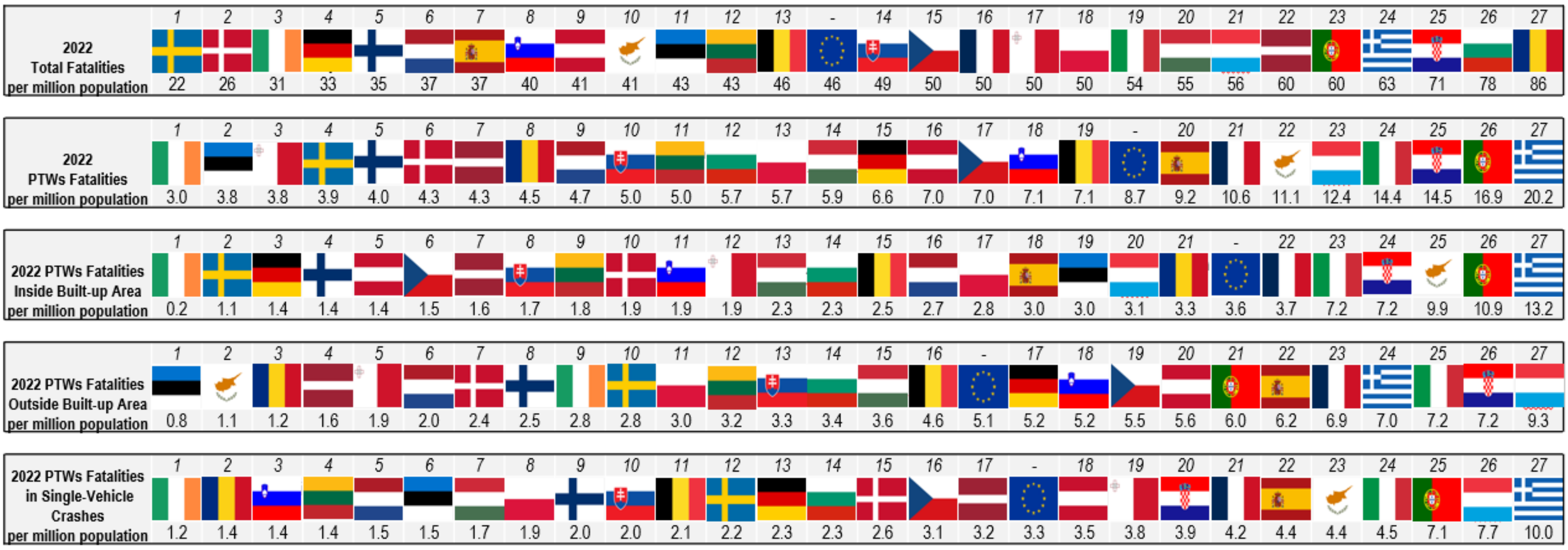
The proportion of PTW fatalities within the total number of road fatalities in the EU in 2022 was 18.8%. Although the number of PTW fatalities decreased by 16.5% between 2012 and 2022, the total number of all road fatalities decreased even more (-22%). As a result, the relative proportion of PTW fatalities within the total number of fatalities has slightly increased.

***Figure 2**. Annual number of PTW rider fatalities, and their share in the total number of fatalities in the EU27 (2012-2022) (Source: CARE).*



The following Figure 3 shows that the mortality rate of PTW fatalities is highest in the southern EU. However, it is important to consider the popularity of these transport modes in the respective countries when interpreting the figures.

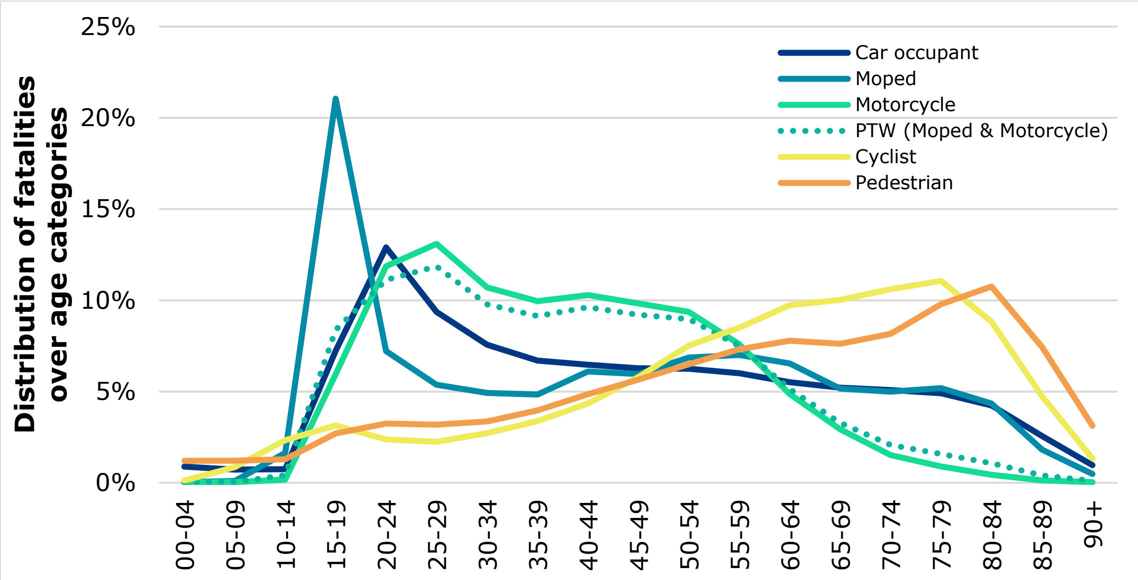
***Figure 3**. PTW fatalities per population ranking (from low to high), EU 2022, (Source: CARE, Processing: NTUA - Road Safety Observatory).*
Notes: 2020 PTWs data for Ireland and Latvia, 2021 PTWs data for Malta



2.3 Crash characteristics

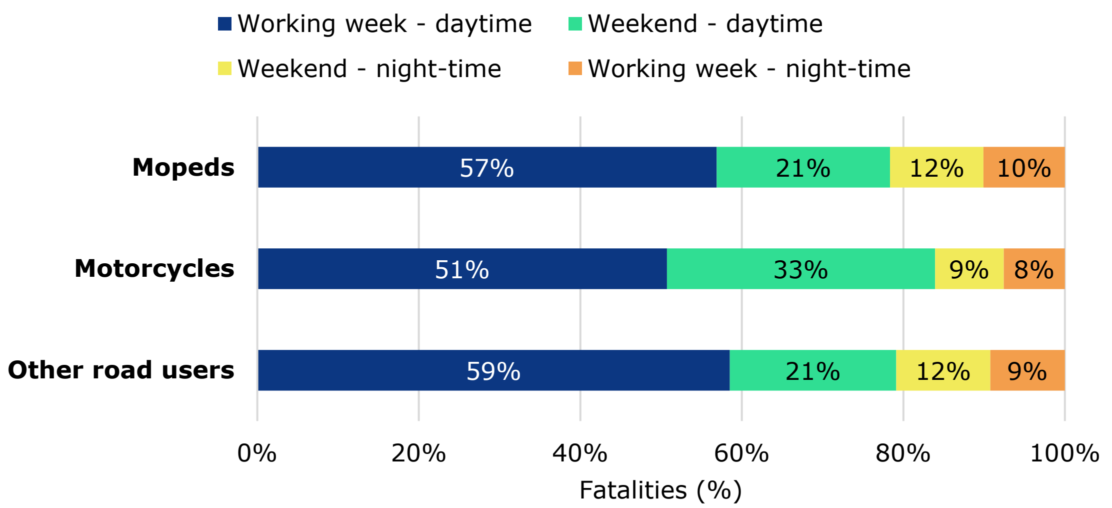
The Figure below provides a more detailed picture of the distribution of PTW fatalities by age categories. For moped riders, the peak age group for fatalities is 15-19 years, accounting for 21%, indicating a high risk among this age group. For motorcycle riders, the fatality rate peaks at 25-29 years at 13%, but the 20-24 age group also shows a high rate at 12%, highlighting significant risk among young adults.

Figure 4. *Distribution of fatalities over 5-year age categories, by transport mode, in the EU27 (2012-2022), (Source: CARE)*



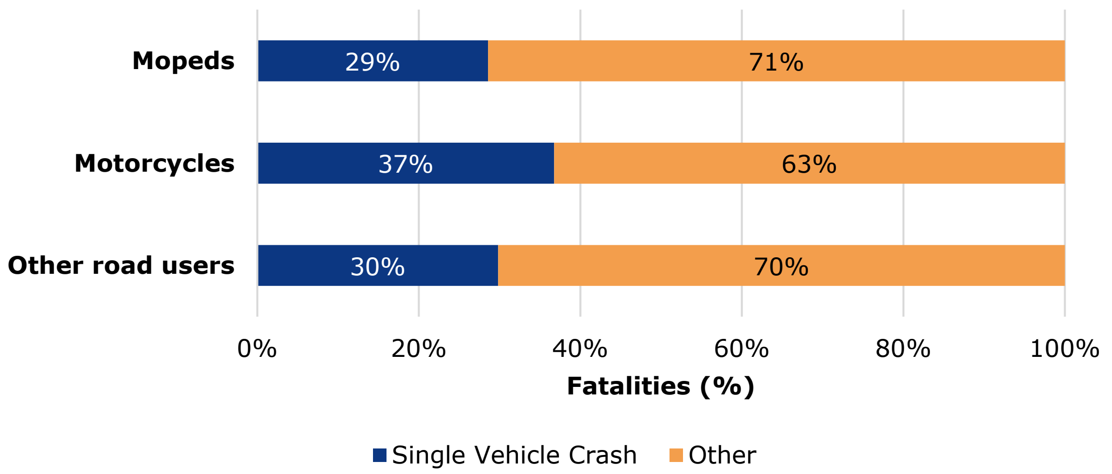
Moped rider fatalities are quite similarly distributed over the course of a week in comparison to fatalities of other road users. Motorcycle rider fatalities are proportionately higher during daytime at the weekend, compared to other road users' fatalities as Figure 5 shows. This difference can probably be explained by differences in the utilisation of modes of transport (European Commission, 2021). Furthermore, car drivers have difficulty detecting and identifying motorcyclists at night, but also in the daytime (Abdul Khalid et al., 2021a).

Figure 5*. Distribution of motorcycle rider, moped rider and other road user fatalities according to period of the week in the EU27 (2022). (Source: CARE)*



The share of moped rider fatalities resulting from a single vehicle crash (29%) is comparable to other road user fatalities (30%) whereas in comparison this crash type occurs more often with motorcycle riders, i.e., 37%.

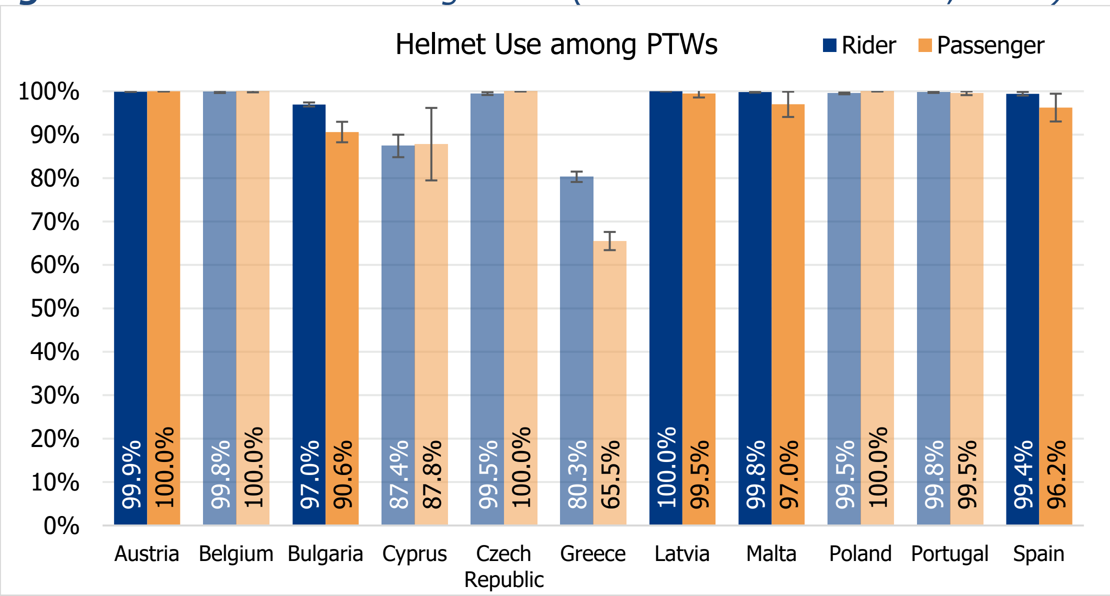
Figure 6*. Distribution of motorcycle rider, moped rider and other road user fatalities by type of collision in the EU27 (2022). (Source: CARE)*



2.4 Helmet use among PTWs

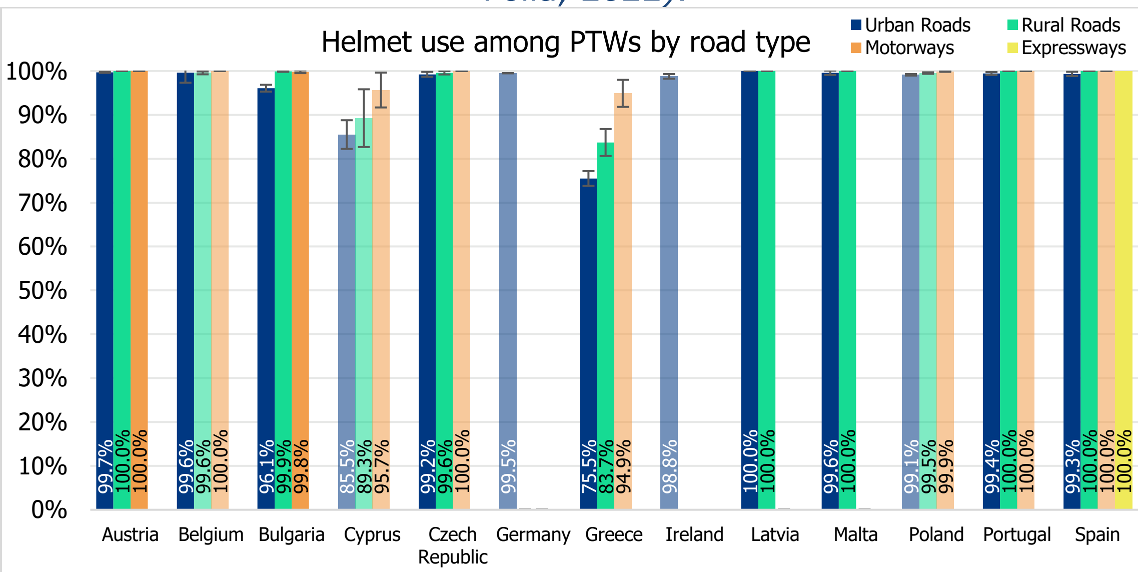
In order to gain a better understanding of the different issues that influence overall road safety performance, the European Commission has elaborated, in cooperation with EU Member State experts, a first set of key performance indicators (KPIs). In the following Figures, information on the KPI "helmet use" among PTWs, that were collected within the framework of the Baseline Project are provided (Yannis & Folla, 2022).

***Figure 7**. Helmet use among PTWs (Source: Yannis & Folla, 2022).*



*Note: Countries with deviations in the methodology are shown with light colours (no weighting for Poland / Minimum total sample size not achieved for Belgium and Cyprus/ Minimum sample size for motorways not achieved for Czech Republic, Greece and Portugal)

***Figure 8**. Helmet use among PTWs by road type (Source: Yannis & Folla, 2022).*



*Note: Countries with deviations in the methodology are shown with light colours (Minimum sample requirements not achieved for motorways of Belgium, Cyprus, Czech Republic, Greece, Portugal / no weighting for Germany, Ireland and Poland)

It can be observed that in almost all countries, helmet use is very high (>95%) for both riders and passengers, except for Greece, where only 80.1% of riders and 63.5% of passengers use a helmet when riding a PTW, followed by Cyprus.

With respect to different road types, in most of the countries, the prevalence of helmet use is almost the same on motorways and rural roads, except Greece. In Bulgaria and Greece, KPIs on urban roads are lower than those observed on the other types of roads, with the highest difference being identified in Greece (only 76% of riders use helmet when travelling on urban roads).

2.5 Crash causation factors

2.5.1 Factors related to road users

Collisions between PTWs and passenger cars usually happen because the PTW rider has been overlooked. The important issue, therefore, as far as the other road user is concerned, is that of perception (ACEM, 2009; SWOV, 2017). The approaching speed and distance of the rider are also often underestimated (ACEM, 2009, Huertas- Leyva et al., 2021). Since PTW riders can overtake in situations where cars cannot, other road users might not expect them in areas where they would not normally look for cars (European Commission, 2018; IRAP, 2022a). Being less conspicuous, PTWs themselves also contribute to being overlooked (Huertas-Leyva et al., 2021). Low expectations of potential problems among some PTW riders can lead to speeding and risk-taking, thus increasing the likelihood of crashes. In the MAIDS study, speed was identified as a causal factor in 21% of cases (ACEM, 2009).

Young age of PTW riders and lack of rider training and experience also play a role in PTW crashes (Möller et al. 2020). Young males especially have a strong propensity for risky behaviour, which increases the risk of crashes. Overconfidence is a primary cause of risky riding behaviour of young riders (Vlahogianni et al., 2012). There are different types of experience: years of riding, familiarity with a specific PTW or with specific conditions. Every type of experience will impact the crash rate to some extent (European Commission, 2018).

Behavioural issues are major moderating factors in PTW crashes. Risk taking and sensation seeking are typical behaviours of riders, often manifested through speeding, disobeying traffic signals and signs, ignoring overtaking restrictions or pedestrian crossings, maintaining short gaps with following vehicles, usual lane sharing etc. (Gupta et al., 2024; Vlahogianni et al., 2012).

The effect of alcohol on car drivers is well known: drink-driving increases the likelihood of engaging in risk-taking behaviour, which leads to a higher crash risk for the alcohol-impaired driver. However, research on the impact of alcohol on PTW riders is lacking. The few studies that have been conducted show that increased blood alcohol levels lead to increased driving errors, especially "running off the road", significant changes in vehicle controlling skills, lengthening of brake reaction time, and an increase in the standard deviation from lateral position (Vu et al., 2020).

2.5.2 Factors related to the vehicle

Some vehicle design elements, such as frame, suspension, wheels, brakes, and tyres, are relevant for PTW safety (European Commission, 2018). Certain manoeuvers carry a higher risk for PTW riders than for car drivers. For example, riding a PTW involves body movement and countersteering and is therefore less stable specifically at low speeds, meaning riders are more likely to lose control of their vehicle while cornering (IRAP, 2022a).

Braking is difficult for several reasons. Because a PTW has only two wheels in line, it is easy to lose friction between tyres and road surface, resulting in a fall, most often while braking in a curve. If the front wheel locks during braking, the stabilizing effect of the spinning wheel disappears and the PTW rider can fall or start skidding (European Commission, 2018; SWOV, 2017). The Anti-Lock Braking System (ABS) on motorcycles – which prevents the wheels from locking while braking hard - has been a significant improvement for motorcycle safety. Specifically, the effectiveness of motorcycle ABS in reducing injury crashes ranged from 24% in Italy (2009) to 29% in Spain (2006-2009), and 34% in Sweden (2003-2012). The reductions in severe and fatal crashes were even greater, at 34% in Spain and 42% in Sweden (Rizzi et al., 2015).

Other factors that can contribute to a loss of control are: wet or oily roads, loose material on the ground, and suddenly appearing obstacles that lead to avoidance manoeuvres (European Commission, 2018).

The relationship between PTW type, engine size, and behaviour of the PTW rider is less clear. However, studies suggest that riders of the "sporty" PTW type have a significantly increased risk of serious crashes and, in particular, fatal crashes (ACEM, 2009; Martensen & Roynard, 2013, Dubois et al., 2020).

A higher crash rate for heavy and/or powerful PTWs does not necessarily mean that they are more difficult to control or are less safe vehicles. It is possible that they are used by riders with different styles of riding. Therefore, it is possibly not the character of the PTW but the character, experience and motivation of the rider which determines the safety of the PTW (European Commission, 2018).

2.5.3 Factors related to the road environment

Road environment characteristics affect PTW riders, as the specific nature of riding makes them more sensitive to road difficulties. This increased sensitivity can lead to falls or slips, and often the road environment is "unforgiving" to them because their vulnerability makes them more fragile to obstacles, leading to serious or even fatal injuries. Infrastructure also influences human behaviour: it helps riders control their vehicle, prevents loss of control, and influences interaction with other road users. The following shortcomings in the road environment have a significant influence on the risk of crashes involving PTWs (Delhaye & Marot, 2016; IRAP, 2022a):

- Road surface defects, such as unevenness and potholes.
- Water, oil or moisture on the road.
- Poor road alignment.
- Presence of obstacles, roadside hazards and safety barriers.
- Interaction with larger vehicles.
- Excessive or thick (high) lane markings, use of raised pavement markers, in general all road markings or bituminous road surface fixes with insufficient skid resistance.

Obstacles (such as poles, walls, trees, etc.) can add to the severity of a crash. The impact would have been less severe if these obstacles were absent or shielded (Delhaye & Marot, 2016). The most contentious area of debate are crash barriers, which are typically not tested for their impact on PTW riders (IRAP, 2022a) and are designed to prevent cars from colliding with obstacles behind the rail, but they do not take into account collisions with PTWs. A PTW rider colliding with an unprotected crash barrier can cause severe injuries (SWOV, 2017; European Commission, 2018).

3. Countermeasures

Countermeasures should take into account the implementation of a rigorous safe system approach, which implies improving infrastructure, enhancing vehicle safety, setting appropriate speeds and behaviour of all road users and adequate enforcement.

3.1 Safer road users

3.1.1 Licensing and training

Pre-licence training should aim at teaching the necessary knowledge and skills, but also the mental attitude to ride defensively and be aware of risk exposure. Training in ABS operation and knowledge of ABS are also important. New simulation techniques offer new opportunities for training programs for PTW riders (Delhaye & Marot, 2016). Because the effects and efficiency of pre-license training have not yet been ascertained, any new programs in this area should be evaluated.

In the European Initial Rider Training Project, a 3-part curriculum was compiled in collaboration with the European motorcycle associations. The theoretical module should cover traffic rules and road signs, the mechanical and dynamic aspects of a motorcycle, the perception of dangerous situations, wearing protective clothing, social responsibility (e.g., avoiding noise pollution), and the role of alcohol, drugs, and fatigue. The necessity of a defensive driving style, in which the rider also anticipates possible errors of other road users, is also important. The second module is dedicated to motorcycle control, in which the students have to familiarize themselves with the machine, try out first movements, shifting, braking and changing direction, practice manoeuvres at low speeds, and also practice manoeuvres in certain emergency situations. The third module is about participating in traffic, in which proper positioning, correct distance and appropriate speed in various situations are practised, e.g., in turns, at intersections, when overtaking, and riding on motorways. Here also the emphasis should be placed on anticipation (European Union, 2011).

Attention should also be paid to training car drivers during their driving licence training to detect, notice and identify approaching PTWs when crossing a road (Slootmans et al., 2017).

3.1.2 Promotional campaigns

There is a link between the PTW type and the motive of the rider, the experience they seek and their concept of riding. Persuasive communication, tailored to the requirements of the average ride of a PTW type, could be provided when buying a PTW so as to encourage safe riding behaviour (Delhaye & Marot, 2016).

3.1.3 Helmets and protective clothing

Protective clothing shields the rider against abrasion and reduces the risk of burns from contact with hot metal. It even reduces the severity of fractures and the risk of infection from road dirt in the case of open wounds (IRAP, 2022b). In low and middle-income countries, the proportion of PTW riders wearing protective clothing is low because of high cost and perceptions of discomfort (e.g., in a warm climate).

In these countries, it is best to focus on helmet-wearing rates, legislating for compulsory helmet-wearing (including enforcement) for all riders, and promoting improvements in the quality of helmets. In countries with high helmet-wearing rates, it is better to invest in public education campaigns about protective clothing. In these campaigns, the protective value of such clothing should be highlighted, and good quality clothing should be clearly described (IRAP, 2022b).

3.1.4 Enforcement

Police enforcement should focus on the behaviour of all road users, enforcement activities for moped and motorcycle riders should include the use of helmets, speeding and distraction, and , especially in the case of mopeds, engine tuning. A study found that the majority of crashes, involving a moped ridden by a 16- or 17-year-old in Denmark were caused by violation of traffic laws by the moped rider, preventive measures "should aim to eliminate violations and increase anticipatory skills among moped riders and awareness of mopeds among other road users." (Møller & Haustein, 2016).

3.2 Safer vehicles

3.2.1 Conspicuousness of PTW riders

An important reason for PTW riders' poor perceptibility is the comparatively small size of their PTWs in contrast to cars. Moreover, some drivers who only see the headlight of the PTW do not see that they are dealing with a PTW rider and underestimate the time remaining to perform a manoeuvre (Slootmans et al., 2017). Reflectors, bright clothing, and helmets are used by PTW riders in an attempt to make them more conspicuous (Gershon & Shinar, 2013). Some other solutions can help to increase the visibility of PTW riders:

- front lighting that emphasizes the contours of the PTW (for example, additional lights at the ends of the handlebars, or an illuminated fork) (Slootmans et al., 2017).
- an Alternating Blinking Light System that is placed at the top of the helmet, which blinks in an alternating manner. This creates an illusion of movement (Gershon & Shinar, 2013).
- Daytime Running Lights (DRL) have been studied many times, and are found to effectively contribute to better PTW visibility and

detection. However, this effect is hampered when other vehicles also adopt DRL. One solution is to change the DRL color for PTWs, so they can be recognized more easily (Abbul Khalid, 2021a).

- several front light configurations and their effect on conspicuousness have also been studied. PTWs with a T-shaped light configuration are more quickly identified in traffic (Rößger et al., 2012).

Research suggests that PTW riders using alternative light systems were more rapidly recognized as such, but that this effect disappears over time (Rößger et al., 2012; Gershon & Shinar, 2013).

3.2.2 Advanced Rider Assist Systems

Tests have shown that the Advanced Cruise Control (ACC) systems of cars are not able to detect PTWs correctly. Enhancements in the safety characteristics and functional capabilities of modern cars' ADAS systems could help better identify PTWs in traffic (Westerband, 2018). The new EU General Safety Regulation 2019/2144 which introduced state-of-the-art safety technologies as standard vehicle equipment in July 2022, should help improve the safety of vulnerable road users, including moped riders. For example:

- Advanced emergency braking systems capable of detecting motor vehicles and vulnerable road users in front of them.
- Enlarged head-impact protection zones capable of mitigating injuries in collisions with vulnerable road users.
- Cars and vans must be constructed in such a way that will help to reduce blind spots in front of and to the side of the driver.

Compared to passenger cars, the introduction of safety features for PTWs is lagging. Some PTW Advanced Rider Assist Systems (ARAS) could help reduce PTW crashes and fatalities, such as Electronic Stability Control, Forward Collision Warning, Lane Departure Warning, etc. (Abdul Khalid et al., 2021b; IRAP, 2022c). Currently, some ARAS systems are already in use or under development (such as Adaptive Cruise Control), but more research is needed to establish the approximate costs and which safety systems can be realistically transferred to PTWs.

3.3 Safer roads

PTWs are an important mode of transport, and their requirements should be reflected in road design (IRAP, 2022a). Improving the road environment for PTW riders requires a better understanding of PTW riding activity and the actual needs and constraints of PTW riders (Delhaye & Marot, 2016).

Roads should be forgiving: errors are inevitable in the road transport system and should be ameliorated by better design. In the first place, road design should allow adequate room for rectification of any errors (IRAP, 2022d).

Roadside safety design can limit the severity of trauma for PTW riders by providing clear zones of soft ground surface and by removing, relocating, or modifying roadside hazards. Parapets of appropriate design, height, and layout are needed for bridges and along other drops (IRAP, 2022d). Crash barriers should also be improved: secondary rails (such as “BikeGuard”, “BASYC” or “Moto Tub systems”) which protect riders from posts and present a continuous surface should be implemented (IRAP, 2022d).

Moreover, the quality of the road surface is very important for PTW riders. The choice of materials for the road surface, the choice of road markings, and road maintenance and repair are essential for the comfort and safety of PTW riders. Any irregularity in the road surface can be an obstacle and lead to a fall. Road markings, sewer covers, etc. can be slippery in rainy weather (European Commission, 2018; Slootmans et al., 2017).

A more far-reaching solution would be the implementation of separate PTW lanes. These can be inclusive – located outside of the main carriageway for each direction of traffic flow – or exclusive – requiring a carriageway completely separate from the one used by other vehicles. These separate lanes could reduce vehicle-to-PTW crashes by limiting the interaction with heavier vehicles and can improve traffic flow (IRAP, 2022e). However, they would have little effect on single-vehicle crashes at intersections. Further research is needed to determine their effect on the crash risk of PTW riders.

Crashes involving a PTW often happen at intersections, which is why infrastructure-based technologies have the capacity to prevent collisions. Co-operative Intelligent Transport Systems (ITS) should be developed, to enable road users to become aware of the presence of PTWs (Morris et al., 2018). Most innovations in the ITS sector target motorized transport. However, avoiding/mitigating visibility problems (adverse lighting or weather conditions) and counteracting critical infrastructure are ideal applications for ITS (Bell & Risser, 2017).

The most beneficial option is a general speed limit of 30 km/h in urban areas on roads where vulnerable road users share the road with motorised vehicles (Stelling et al., 2021; Yannis & Michelaraki, 2024).

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