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A B S T R A C T

Introduction: The recent increase in the use of bicycles and personal mobility devices (PMDs), including mostly E-scooters, is associated with a rapid rise in injuries. Understanding the main crash scenarios leading to these injuries is essential to evaluate and improve preventive and protective measures, especially for PMDs, which are often equated with bicycles. The objective of this study is to identify and compare the most common two-party collision scenarios for bicycles and PMDs, and to identify factors affecting injury severity. *Method:* Crashes involving at least one PMD or one bicycle and another road user were analyzed from the 2019–2022 French police-reported road crashes database. We investigated the rider, the other vehicle, the road, and the crash scenarios characteristics (pre-crash maneuvers, impact zone on vehicles) and their joint effect on injury severity (hospitalization or fatality: yes/no). *Results:* We included 16,302 bicycle crashes and 4,118 PMD crashes in the analysis. Most of these collisions (75%) were against a car. The most frequent and the most severe collision scenario was the side-on-head for both bicycles (51%) and PMDs (58%); 67% of both bicycles and PMDs were going straight before the collision. Main factors associated with increased injury severity included colliding with a greater size vehicle, age above 50, and riding on roads with a higher speed limit. Bicycles remained at a higher risk of severe injury than PMDs after accounting for adjustment factors. *Conclusions:* Although collision scenarios appear similar for bicycles and PMDs, differences in other crash characteristics and injury severity suggest that these two modes of transportation should not be equated in crash investigations. *Practical implications:* These findings emphasize the need to primarily investigate side-on-head collisions with a moving car for both PMDs and bicycles in order to develop, evaluate, and improve protective devices to reduce the risk of injuries.

1. Introduction

Over the last few years, the use of micromobility vehicles, including bicycles and personal mobility devices (PMDs) such as E-scooters, skateboards, rollers, segways or hoverboards (ONISR, 2022) has been growing strongly worldwide (Coretti Sanchez et al., 2022; Francke, 2022), including in France (Christoforou et al., 2021). This drastic rise has led to an increasing number of road crashes, including collisions and falls, and involving bicycles (Schijndel et al., 2012) and PMDs (Brauner et al., 2022; Mongaillard & Alexandre, 2018; ONISR, 2022; Tark, 2022): +31% for cyclists and +250% for PMDs in 2022 compared to 2019 in France. In 2022 in France, 8% of fatalities and 20% of serious injuries in road crashes affected cyclists and PMD users (ONISR, 2022). Although single falls due to imbalance or poor road conditions account globally for 60% to 95% of all road crashes for both bicycles (Schepers et al., 2015) and PMDs (ONISR, 2022; Singh et al., 2022), collisions with other vehicles are generally associated with more severe injuries (Blaizot et al., 2012; Heesch et al., 2011). For example, cyclists are seven times more likely to be killed in a collision with a motorized vehicle than in the case of a single fall (Blaizot et al., 2012).

For continued improvement in cyclists and PMD users' injury protection, safety devices should be developed and evaluated based on the impacts sustained during collisions against other vehicles. This is especially true for head protection as traumatic brain injuries are the leading cause of death among cyclists and PMD users (James et al., 2023). For bicycle helmets, road crash reconstructions were performed with numerical models (Bourdet et al., 2012; Gao et al., 2020), obtaining detailed information of head impact conditions used for the evaluation of helmets and the development of the EN1078 European standard (EN1078 European Standard, 2012). Numerical reconstructions require detailed descriptions of crash scenarios. For bicycles, such scenarios have already been described. It has been shown that the most frequent collision scenario (42%-78%) occurred when the other road user (ORU) crossed the bicycle path (Billot-Grasset, 2015; Gildea et al., 2021;

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Isaksson-Hellman & Werneke, 2017). Most of the time, neither party involved was changing direction (7%–32%); or the ORU was turning at an intersection (18%-41%) and cutting the cyclist route. In contrast, very few studies have examined E-scooter collisions. To our knowledge, only Shah et al. (2021) provided a detailed description of a cohort of E-scooter and bicycle collisions. While bicycle crashes were distributed over multiple crash typologies, two primary scenarios were identified for E-scooter collisions: the E-scooter approached the motorized ORU while the ORU was either going straight or turning right. However, in this pioneering study, only 52 E-scooter crashes and 79 bicycle crashes were analyzed and the limited available data restricts the global understanding of crash scenarios and the design of accurate accident reconstructions for protective device evaluation. This is critical for PMDs as no specific helmet standard exists and PMD users tend to use bicycle helmets, while there is no evidence that injury mechanisms are the same for bicycles and PMDs. Thus, it is necessary to evaluate whether they can be considered jointly with bicycles when seeking accident prevention and to improve the global understanding of micromobility crash scenarios.

The objective of this study is to identify, describe, and compare collision scenarios involving bicycles and PMDs. The effect of the collision circumstances on injury severity is also investigated. To this end, a national public database completed by French law enforcement authorities is used to compare the circumstances of collisions between bicycles and PMDs. The collision scenarios based on vehicle manoeuvres and impact locations are examined and their respective distributions are compared. Finally, the factors influencing the severity of injuries sustained by cylists and PMD riders are estimated using a multiple logistic regression model.

2. Methods

2.1. Data

This analysis was based on data from the French national road safety database, publicly available and updated each year by the National Interministerial Road Safety Observatory (ONISR). It is filled in by law enforcement officers and includes road crashes involving at least one vehicle and one victim requiring care. The crash information gathered is organized into four sections: road crash general characteristics (date, time, geographical information, weather conditions), road crash location (type of road and infrastructure), vehicles involved (type of vehicles, impacted obstacle, maneuver, impact zone), and users involved (sitting place in the vehicle, age, sex, injuries, safety equipment, etc.). PMDs and bicycles are considered as vehicles. Road crashes are not included in the database when the police did not intervene, when they did not write down a report of the crash, or did not notify it.

In this study, crashes involving at least one PMD or bicycle and one ORU (another vehicle or pedestrian) between 2019 and 2022 were examined. Crashes occurring before 2018 were not included, as limited information about maneuvers, impacts, motorization, and obstacles was collected in the previous years, especially for PMDs. We focused on collisions, which are generally associated with more serious injuries, and did not analyze single falls, as they are rarely reported by police officers (Amoros et al., 2006). Road crashes were excluded if they met any of the following criteria: (1) there was no ORU; (2) there was no collision (e.g., the bicycle or PMD avoided an ORU, resulting in a fall); (3) three or more vehicles were involved (at least 1 bicycle/PMD and 2 ORUs), as the crash circumstances were complex to disentangle; and (4) the bicycle or PMD rider's data was not documented. Crashes with passenger information only were excluded. The number of crashes excluded at each stage is described in the supplementary material (figure S1).

A total of 23 variables were extracted from the database and analyzed in this study including 1 continuous and 22 categorical variables. They are the followings: year of the crash, luminosity, weather condition, if the crash occurred at an intersection, urbanization, road type, collision location, road curvature, road profile, surface condition, micromobility vehicle, ORU type and its moving status, impact zone and maneuver for both the bicycle/PMD and the ORU; bicycle or PMD rider's injury severity, age, sex, helmet use, and reason for moving; presence of passenger on the bicycle/PMD. The categories of the variables are detailed in Table 1. Only the characteristics of the rider were examined, not those of the passengers.

Crashes with a moving vehicle were categorized based on maneuvers and impact scenario as it has been previously done for cyclist-motorized vehicle collisions (Gildea et al., 2021). For this analysis, the maneuver "crossing the road" was categorized under "no change of direction," and the maneuvers "turning" and "changing lane" were combined under "changing direction" to reduce the number of categories. This was done because we assume that the associated kinematics are similar. The impact scenarios between the bicycle or PMD and the other moving vehicle were clustered into six categories based on the impact zone on both vehicles (see drawings of these scenarios in Fig. 1). The name of each category describes the impact zone on the bicycle/PMD in first and the impact zone on the ORU in second: head-on-side (frontal impact for the bicycle or PMD and lateral impact for the ORU), head-on-rear (frontal impact for the bicycle or PMD and posterior impact for the ORU), side-on-head (lateral impact for the bicycle or PMD and frontal impact for the ORU), rear-end (posterior impact for the bicycle or PMD and frontal impact for the ORU), head-on (frontal impact for both vehicles), and sideswipe (lateral impact for both vehicles). Because the angle of impact with the ORU was not specified, it was difficult to distinguish between a side-on-head and a head-on scenario when the bicycle or the PMD collided with the corner of the moving vehicle. In such cases, the label side-on-head was chosen. Collisions with pedestrians and stationary vehicles were treated apart, as no maneuver is associated with the ORU in those cases.

2.2. Statistical analyses

First, descriptive analyses to compare bicycles and PMDs crashes were conducted. Continuous variables distribution was displayed as medians and quartiles, and the distribution of categorical variables as total counts and percentages for both categories. For numeric and categorical variables, the Wilcoxon-Mann-Whitney and chi-square tests were respectively used to compare the PMD and bicycle groups. Statistical tests were computed independently for each category of a given variable. For example, for the type of ORU, we compared the percentages of pedestrian and non-pedestrian ORUs in the bicycle and the PMD groups, and we repeated the test separately for car and non-car ORUs, motorcycle and non-motorcycle ORUs, and so forth. A significance threshold of 0.05 was used. To measure the association between each categorical variable and the bicycle or PMD groups, the Cramer's V (V) metric was employed. This statistical method tests the strength of association between two categorical variables, providing a value between 0 (no association) and 1 (full association). This metric was chosen due to large sample sizes, making even small effects significant. The present study considers a V value less than 0.1 as indicating a weak association between variables, while a V value greater than 0.2 indicates a strong association.

Second, factors influencing the severity of injuries among cyclists and PMD riders were investigated. A multivariate logistic regression analysis was conducted. The outcome variable was injury severity, categorized into two categories: "minor injury" for uninjured or slightly injured and "severe injury" for hospitalized or killed. First, the association between each pair of explanatory variables was measured using Cramer's V to avoid collinearity in the logistic regression model. Weather condition, road type and urbanization were excluded from the analysis due to their strong association with surface status (V=0.68 for whether condition) and speed limit (V=0.30 for road type and V=0.80 for urbanization). All the other variables listed above were included as

Table 1
Characteristics comparison of PMD and bicycle collisions. ORU=other road user; PMD=personal mobility device; [a] national/departmental; [b] Q1, Q3 = first and third quartiles; [c] P_W = P-value of the Wilcoxon-Mann-Whitney test. Cramer's V (V) indicates the strength of association between each variable and bicycle or PMD groups; Significant differences calculated using the chi-square test are indicated with * ($p < 0.05$) or ** ($p < 0.001$).

Characteristic	Bicycle (n = 16,302)	PMD (n = 4,118)	V	Characteristic	Bicycle (n = 16,302)	PMD (n = 4,118)	V
Year				**ORU moving status**			
2019**	3,748 (23.0%)	505 (12.3%)	0.11	Moving vehicle*	13,623 (83.6%)	3,388 (82.3%)	0.01
2020**	3,700 (22.7%)	734 (17.8%)	0.05	Stationary vehicle**	1,143 (7.0%)	198 (4.8%)	0.04
2021**	4,423 (27.1%)	1,261 (30.6%)	0.03	Pedestrian**	1,025 (6.3%)	404 (9.8%)	0.06
2022**	4,431 (27.2%)	1,618 (39.3%)	0.11	Other	511 (3.1%)	128 (3.1%)	<0.01
Luminosity				**Impact zone on bicycle /PMD**			
Daylight**	12,960 (79.5%)	3,012 (73.1%)	0.06	Head**	9,928 (60.9%)	2,794 (67.8%)	0.06
Darkness**	3,341 (20.5%)	1,106 (26.9%)	0.06	Side	4,188 (25.7%)	1,070 (26%)	<0.01
NA	1 (<0.1%)	0	–	Rear**	2,110 (12.9%)	240 (5.8%)	0.09
Weather condition				Other/NA	76 (0.5%)	14 (0.4%)	<0.01
Favorable	13,689 (84%)	3,448 (83.7%)	<0.01	**Impact zone on ORU**			
Adverse	2,579 (15.8%)	662 (16.1%)	<0.01	Head	11,155 (68.4%)	2,781 (67.5%)	0.01
Other/NA	34 (0.2%)	8 (0.2%)	–	Side	2,362 (14.5%)	571 (13.9%)	0.01
Intersection				Rear**	1,742 (10.7%)	358 (8.7%)	0.03
Yes**	8,921 (54.7%)	2,418 (58.7%)	0.03	Not applicable/NA**	1,043 (6.4%)	408 (9.9%)	0.06
No**	7,032 (43.1%)	1,570 (38.1%)	0.04	**Maneuver of bicycle/PMD**			
NA**	349 (2.1%)	130 (3.2%)	0.03	No change**	9,848 (60.4%)	2,107 (51.2%)	0.08
Urbanization				Crossing the road**	1,527 (9.4%)	651 (15.8%)	0.08
Urban area**	14,048 (86.2%)	4,018 (97.6%)	0.14	Changing lane	1,764 (10.8%)	401 (9.7%)	0.01
Rural area**	2,254 (13.8%)	100 (2.4%)	0.14	Turning**	1,194 (7.3%)	229 (5.6%)	0.03
Road type				Other/NA**	1,969 (12.1%)	730 (17.7%)	0.07
Municipal**	11,064 (67.9%)	3,205 (77.8%)	0.09	**Maneuver of ORU**			
Nat./dep**[a]	5,032 (30.9%)	852 (20.7%)	0.09	No change**	6,117 (37.5%)	1,650 (40.1%)	0.02
NA	206 (1.3%)	61 (1.5%)	0.01	Crossing the road	306 (1.9%)	88 (2.1%)	<0.01
Collision location				Changing lane**	2,964 (18.2%)	544 (13.2%)	0.05
Road 50 km/h	8,586 (52.7%)	2,166 (52.6%)	<0.01	Turning	3,533 (21.7%)	901 (21.9%)	<0.01
Road < 50 km/h**	2,625 (16.1%)	826 (20.1%)	0.04	Other/NA	3,382 (20.7%)	935 (22.7%)	0.01
Road > 50 km/h**	1,808 (11.1%)	63 (1.5%)	0.13	**Rider's Injury severity**			
Cycle path	2,446 (15.0%)	659 (16.0%)	0.01	Uninjured**	1,308 (8.0%)	524 (12.7%)	0.07
Sidewalk**	231 (1.4%)	207 (5.0%)	0.10	Slightly injured**	10,866 (66.7%)	3,019 (73.3%)	0.06
Other/NA**	606 (3.7%)	197 (4.8%)	0.02	Hospitalized**	3,690 (22.6%)	536 (13.0%)	0.10
Road curvature				Killed**	434 (2.7%)	38 (0.9%)	0.05
Straight**	13,672 (83.9%)	3,668 (89.1%)	0.06	NA	4 (<0.1%)	1 (<0.1%)	–
Curved**	2,474 (15.2%)	436 (10.6%)	0.05	**Rider's sex**			
NA	156 (1.0%)	14 (0.3%)	0.01	Male**	12,317 (75.6%)	2,909 (70.6%)	0.04
Road profile				Female**	3,874 (23.8%)	1,137 (27.6%)	0.04
Flat**	13,276 (81.4%)	3,599 (87.4%)	0.06	NA**	111 (0.7%)	72 (1.7%)	0.05
Inclined**	3,024 (18.5%)	518 (12.6%)	0.06	**Rider's age**			
NA	2 (<0.1%)	1 (<0.1%)	–	Median (Q1;Q3)[b]	38 (24; 55)	26 (20; 37)	$P_W < 0.001$[c]
Surface condition				<18**	1,950 (12%)	703 (17.1%)	0.06
Normal*	14,267 (87.5%)	3,547 (86.1%)	0.02	18–29**	3,984 (24.4%)	1,691 (41.1%)	0.15
Slippery*	2,030 (12.5%)	570 (13.8%)	0.02	30–49**	4,791 (29.4%)	1,288 (31.3%)	0.02
NA	5 (<0.1%)	1 (<0.1%)	–	>50**	5,461 (33.5%)	364 (8.8%)	0.22
Motorization				NA**	116 (0.7%)	72 (1.7%)	0.04
Non-motorized**	13,512 (82.9%)	492 (11.9%)	0. 61	**Rider's helmet use**	231 (1.4%)	207 (5.0%)	
Electric**	1,297 (8%)	3,617 (87.8%)	0.75	Yes**	7,487 (45.9%)	1,087 (26.4%)	0.16
NA**	1,493 (9.2%)	9 (0.2%)	0.14	No**	7,806 (47.9%)	2,595 (63%)	0.12
ORU				NA**	1,009 (6.2%)	436 (10.6%)	0.07
Truck/bus**	654 (4%)	109 (2.6%)	0.03	**Reason for moving**			
Car	12,203 (74.9%)	3,045 (73.9%)	<0.01	Leisure/shopping**	7,098 (43.5%)	1,260 (30.6%)	0.12
Motorcycle	1,077 (6.6%)	244 (5.9%)	0.01	Professional**	3,542 (21.7%)	1,148 (27.9%)	0.09
Bicycle	879 (5.4%)	200 (4.9%)	0.01	Other/NA**	5,662 (34.7%)	1,710 (41.5%)	0.04
PMD	198 (1.2%)	53 (1.3%)	<0.01	**Passenger**			
Pedestrian**	1025 (6.3%)	404 (9.8%)	0.06	Yes**	132 (0.8%)	209 (5.1%)	0.13
Other/NA**	266 (1.6%)	63 (1.5%)	0.02	No/NA**	16,170 (99.2%)	3,909 (94.9%)	0.13

explanatory factors. For each variable, we chose as reference category in the model (used as the basis for comparison with other categories) the one with the highest number of observations. As information on vehicle speed is not available in the database, we used in this analysis the road speed limit as a proxy of the vehicle speed at the moment of the collision. Pedestrian collisions were excluded from the model as no maneuver or impact zone were attributed to those road users. Collisions where the rider's injury severity was not registered were also excluded. Imputation was performed for 11 variables out of the 17 explanatory factors used in the model. The variable with the highest percentage of missing data was "reason for moving" with 25.3% of observations missing. The remaining variables had less than 7% missing observations. Missing observations for explanatory factors were imputed using the method of chained equations, with the mice package in R (version 4.2.3). A total of 5 imputed datasets were generated and used for the multivariate logistic regression. Regression outputs were then aggregated using Rubin's rules (Rubin, 2018). Data processing and analysis were conducted using Rstudio version 2023.09.1 – © 2009–2023 – Posit Software, PBC and Microsoft Office Excel 2019.

3. Results

3.1. Collisions and population characteristics

The database contained 22,749 bicycle and 5,870 PMD road crashes that occurred between 2019 and 2022. The number of PMD crashes

registered in the database has tripled during the study period, from 875 in 2019 to 2,598 in 2022. A total of 16,302 bicycle and 4,118 PMD collisions met the inclusion criteria; their characteristics are given in Table 1.

Focusing on collision characteristics, cars were the most common ORU for both bicycles and PMDs groups, accounting for 74.9% of collisions involving bicycles and 73.9% of collisions involving PMDs. Riders were more often males than females for both groups (bicycle: 75.6% and PMD: 70.6%). Beyond this, bicycle and PMD collisions were significantly different on many aspects (Table 1). Indeed, PMD crashes occurred more often in urban area (97.6% vs 86.2%; $p < 0.001$; V=0.14), on municipal roads (77.8% vs 67.9%; $p < 0.001$; V=0.09), and on sidewalks (5.0% vs 1.4%; $p < 0.001$; V=0.10) compared to bicycle crashes; and they more frequently involved pedestrians (9.9% vs 6.3%; $p < 0.001$; V=0.06). The rear was less often collided on PMDs than on bicycles (5.8% vs 12.9%; $p < 0.001$; V=0.09). In comparison to bicycles, PMDs were crossing the road more often at the time of the collision (15.8% vs. 9.4%; $p < 0.001$; V=0.08) and were going straight ahead less often (51.2% vs. 60.4%; $p < 0.001$; V=0.08). In terms of injury severity, PMD riders were less often hospitalized (13.0% vs. 22.6%; $p < 0.001$; V=0.10) or killed (0.9% vs. 2.7%; $p < 0.001$; V=0.05) than cyclists. PMD riders were younger (median age of 26 vs. 38 years old; $p < 0.001$), they wore less frequently helmets (26.4% vs. 45.9%; $p < 0.001$; V=0.16), and traveled less frequently for shopping or leisure (30.6% vs. 43.5%; $p < 0.001$; V=0.12). Passengers were significantly more frequent on PMDs than on bicycles (5.1% vs 0.8%; $p < 0.001$; V=0.13).

3.2. Collision scenarios

To study the collision scenarios, all crashes in which the impact zone (on the bicycle or PMD and on the ORU) and the maneuvers were documented were included. The information was available for 95% of the collisions with a moving vehicle, resulting in an analysis of 12,906 bicycle and 3,215 PMD road crashes. The most frequent scenario for both bicycle and PMD crashes was a side impact, with the ORU striking the bicycle or the PMD on its side (side-on-head scenario), accounting for 51.0% of bicycle crashes and 58.0% of PMD crashes (Fig. 1). There were no significant difference in scenario frequency between both modes, or the difference was low ($P>0.05$ or $V<0.1$), except for the rear-end scenario, which displayed higher prevalence among bicycles in contrast to PMDs (12.3% vs. 5.2%; $p < 0.001$; V=0.26). The other scenarios for both bicycle and PMD groups combined are 10.6% head-on, 8.8% head-on-side, 9.0% head-on-rear, and 5.6% sideswipe.

For all impact locations combined, further inspection of the maneuvers revealed that when they did not change direction, the PMDs were crossing the roadway significantly more often than the bicycles (27.0% vs. 15.3%; $p < 0.001$; V=0.29). When they were changing direction, they were changing lane (bicycles: 57.4%; PMDs: 60.4%, $p = 0.20$; V=0.02) or turning (bicycles: 42.6%; PMDs: 39.6%; $p = 0.20$; V=0.02). Other maneuvers of the bicycles and PMDs (not classified as “no change of direction” or “changing direction”) were mainly riding wrong way (409 bicycles and 177 PMDs) and riding on the sidewalk (165 bicycles and 123 PMDs). Regardless of the maneuver of the bicycle or PMD, when the ORU changed its direction, it changed lanes 45.0% of the time against bicycles and 37.3% of the time against PMDs, and it turned right or left 55.0% of the time against bicycles and 62.7% of the time against PMDs ($p < 0.001$; V=0.06).

A parked or stationary vehicle was involved in 7.0% (1,143 cases) of all bicycle collisions and 4.8% (198 cases) of all PMD collisions ($p < 0.001$; V=0.04). Most often the bicycles and PMDs did not change direction (bicycles: 81.1%; PMDs: 72.3%; $p = 0.006$; V=0.07).

There were 1,025 bicycle and 404 PMD collisions with pedestrians, which accounted for 6.3% of all bicycle collisions and 9.8% of all PMD collisions ($p < 0.001$; V=0.06). Most often the bicycles and PMDs did not change direction (bicycles: 78.9%; PMDs: 70.2%; $p < 0.001$; V=0.11). These crashes occurred primarily on roads with a speed limit of 50 km/h (bicycles: 29.6%; PMDs: 21.5%; $p = 0.002$; V=0.08), followed by bicycle paths (bicycles: 33.5%; PMDs: 32.2%; $p = 0.64$; V=0.01) and roads with a speed limit below 50 km/h (bicycles: 22.1% and PMDs: 19.3%; $p = 0.23$; V=0.03).

3.3. Factors affecting injury severity

For the study of factors affecting injury severity, 18,990 crashes were analyzed with 757 uninjured (565 bicycle and 192 PMD riders), 13,571 slightly injured (10,618 bicycle and 2,953 PMD riders), 4,193 hospitalized (3,662 bicycle and 531 PMD riders), and 469 killed riders (431 bicycle and 38 PMD riders). Fig. 3 displays the results of the logistic model adjusted for covariates that evaluates the risk of sustaining a severe injury (defined as being hospitalized or killed) during the collision.

All other parameters being equal, riding an electric PMD or a non-motorized PMD decreased the risk of severe injury compared to riding a conventional bicycle, with odds ratios (ORs) of 0.86 (95% confidence intervals (95%CI), 0.77–0.97) and 0.75 (95%CI, 0.58–0.97, Fig. 3), respectively. Riding an e-bike, on the contrary, increased the risk of severe injury compared to riding a conventional bicycle (OR=1.23, 95% CI, 1.06–1.42).

Compared to crashes on roads with a speed limit of 50 km/h, crashes on roads exceeding this limit were four times more likely to result in a severe injury, and the risk was reduced by 20% on roads with a speed limit below 50 km/h. Crashes on cycle lanes were associated with a 40% reduction in the risk of severe injury compared to crashes on 50 km/h roads. Compared to hitting a car, cyclists and PMD riders faced a significantly lower risk of severe injuries when hitting a PMD, a bicycle, or a motorcycle, but the risk was 2.84 times higher when colliding with a bus or truck (95%CI, 2.40–3.36). Colliding a parked or stationary vehicle displayed a lower risk of severe injuries.

Riders above 50 years old or under 18 years old had an increased risk of severe injury compared to 18–29 years old riders. When a passenger was on the bicycle or the PMD, the rider had a lower risk of being hospitalized or killed. The risk was higher when traveling for shopping or leisure than while commuting from home to work or school. Female riders, and those wearing a helmet had a lower risk of being hospitalized or killed, respectively, compared to males and non-helmeted riders.

Riders had a higher severe injury risk when they were on an inclined road compared to a flat road or on a curved road compared to a straight road. All other variables being equal, crashes in the darkness led to a higher risk of severe injury compared to crashes in daylight. On dry road the risk was also higher than on slippery roads. For the ORU maneuvers the risk of being hospitalized or killed for the rider was 1.25 times higher (95%CI, 1.15–1.35) when it continued straight on compared to when the ORU changed direction. The risk of severe injury was reduced in sideswipe cases in comparison to side-on-head impacts. No significant association with severe injury was found for the different maneuvers of the bicycles or PMDs and for the intersection, when accounting for the other parameters.

4. Discussion

The study of bicycle and PMD collision circumstances performed on an extensive dataset revealed a rather similar distribution of collision scenarios between bicycles and PMDs, and a major collision scenario involving a side-on-head impact (head of the ORU hitting the side of the bicycle/PMD), accounting for more than half of the collisions. Adjusting for collision scenarios and for other adjustment factors, we found that bicycles collisions were associated with a greater risk of severe injuries compared to PMD collisions.

Regarding the maneuvers before collision, we found that the bicycle did not change direction in 66.6% of bicycle crashes and the PMD in 67.7% of PMD crashes (while the ORU could change direction or not). Similar behavior was also noted in prior research on bicycle crashes, where the majority of collisions (77% to 90%) occurred when the bicycle

was going straight (Bahrololoom et al., 2020; Billot-Grasset, 2015). The most prevalent road crash scenario accounting for more than half of the PMD and bicycle collisions was a side-on-head collision where the bicycle or PMD was going straight and the ORU was either traveling straight or changing direction (Figs. 1 and 2). This suggests that the crash occurs when the vehicles cross each other's route, a pattern that is in line with earlier research on bicycle (Isaksson-Hellman & Werneke, 2017; Shah et al., 2021) and E-scooter crashes (Shah et al., 2021). In our study, side-on-head was found to have the higher risk of severe injury, while sideswipe impact scenario the lowest (Fig. 3): side-on-head collisions had a 34% increased risk to lead to severe injury for the rider compared to sideswipe collisions. The overall relationship between collision scenarios and injury severity is actually debated in the literature: according to Kim et al. (2007), head-on collisions are the most dangerous scenario, whereas it is the side-on-head for Moore et al. (2011). On the one hand, the impact velocity in head-on scenarios is the sum of the velocity of the two vehicles; on the other hand, in side-on-head collisions, the vehicles may not perceive each other, reducing the likelihood of braking or having avoidance reflexes. Regarding the ORU maneuvers, a change of direction of the ORU resulted in our study in a lower risk of hospitalizations and fatalities for the rider. This is likely due to the lower speed of the ORU in this situation (Lin & Fan, 2021). The rear-end impacts represented the second most common scenario, accounting for around 10% of collisions. We found that the primary ORU in both PMD and bicycle collisions was car, accounting for three out of four cases in each mode, followed by pedestrians, motorcycles, bicycles, and trucks. These trends are consistent with previously established patterns in bicycle crashes (Billot-Grasset, 2015; Otte & Facius, 2020). Finally, we have shown that collisions scenarios of PMD riders and cyclists are largely alike. Despite the comparable nature of the situations, variations in posture and speed can affect the associated kinematics, human body impact conditions and therefore the severity of injuries. To better understand the effect of these parameters, accident reconstruction, such as multi-body simulations, or full-scale experimental tests would be needed (Ballester et al., 2019; Serre et al., 2007). Our findings on the distribution of crash scenarios suggest that side-on-head collisions would be the primary configuration to investigate.

Although we considered in this study all injuries and not specifically head injuries, previous studies have shown that the head is the most seriously injured body region for both cyclists and E-scooter riders (James et al., 2023). In the studied database, only 26.4% of registered PMD riders and 45.9% of registered cyclists wore a helmet. In our study as in the literature, wearing a helmet decreased the risk of severe injury (Bahrololoom et al., 2020; Boufous et al., 2012). In France, only cyclists under the age of 12 are required to wear a helmet. Høye (2018) conducted a *meta*-analysis and found that mandatory bicycle helmet laws for all cyclists led to a significant 20% reduction in head injuries and a 50% reduction in serious head injuries. Therefore, an efficient way to reduce severe injuries could be to increase the use of head protective devices such as helmets for both cyclists and PMD riders. However, no specific helmet standards exist for PMD riders and they are currently wearing bicycle helmets. Future research should hence investigate specific head impact conditions of PMD users during crashes. To our knowledge three studies have investigated head impacts during E-scooter crashes, and focused mainly on single falls induced by a curb or pothole. They showed that head impact velocities were similar to those observed in bicycle falls or those used in bicycle helmet standards testing protocols (Fournier et al., 2023; Posirisuk et al., 2022; Wei et al., 2023). However, Wei et al. (2023) further found that during this type of fall, the majority of head injury metrics (head linear acceleration, angular velocity, HIC_36, and BrIC) were above the threshold for severe head injuries, even with a bicycle helmet. Current bicycle helmets would thus not be suitable for e-scooter users. The literature lacks information on impact conditions on the human body during collisions involving PMDs. Existing crash reconstruction studies do not cover all crash scenarios brought out in our study. Further research studying these impact conditions is hence crucial to guide the development of future protective devices, including helmets and inflatable solutions. Airbags are emerging as a promising option to extend the protective capabilities of helmets, for example by covering the neck and chest in addition to the head, and increase the protection against impacts due to its higher absorption capacity (Kurt et al., 2017; In&motion, 2023).

Bicycle (N=12,906)
PMD (N=3,215)

	Head-on		Head-on-side		Head-on-rear		Side-on-head		Rear-end		Sideswipe		Other		Total	
	Bicycle	PMD	Bicycle	PMD	Bicycle	PMD	Bicycle	PMD	Bicycle	PMD	Bicycle	PMD	Bicycle	PMD	Bicycle	PMD
No change of direction	2.6%	3.3%	2.2%	3.5%	2.9%	2.5%	15.0%	21.4%	6.2%	2.6%	1.3%	1.2%	0.9%	0.7%	31.1%	35.3%
Both change direction	0.6%	0.5%	0.6%	0.7%	0.5%	0.4%	3.8%	3.0%	1.2%	0.6%	1.0%	0.5%	0.3%	0.2%	8.0%	5.9%
Only bicycle/PMD changes direction	1.6%	1.6%	0.8%	0.9%	0.5%	0.5%	5.8%	5.3%	1.5%	0.6%	0.8%	0.5%	0.2%	0.1%	11.2%	9.5%
Only ORU changes direction	3.7%	3.3%	3.0%	2.9%	2.8%	2.6%	20.8%	19.4%	3.1%	0.8%	2.3%	1.4%	1.0%	0.9%	36.6%	31.3%
Other maneuvers	2.3%	3.6%	0.9%	1.5%	1.4%	1.1%	6.7%	10.0%	0.9%	0.8%	0.5%	0.4%	0.5%	0.4%	13.1%	17.9%
Total	10.3%	12.0%	8.4%	10.5%	9.2%	7.9%	51.0%	58.0%	12.3%	5.2%	6.0%	4.1%	2.9%	2.4%	100%	100%

Fig. 1. Bicycle and PMD collision scenarios against a moving vehicle. The rows indicate the maneuvers of the bicycle or PMD and the other moving vehicle (ORU not including pedestrian and parked/stationary vehicles), while the columns display the impact zones: bicycle/PMD –on- ORU. The gauges are normalized based on the occurrence of the major scenario (21.4%).

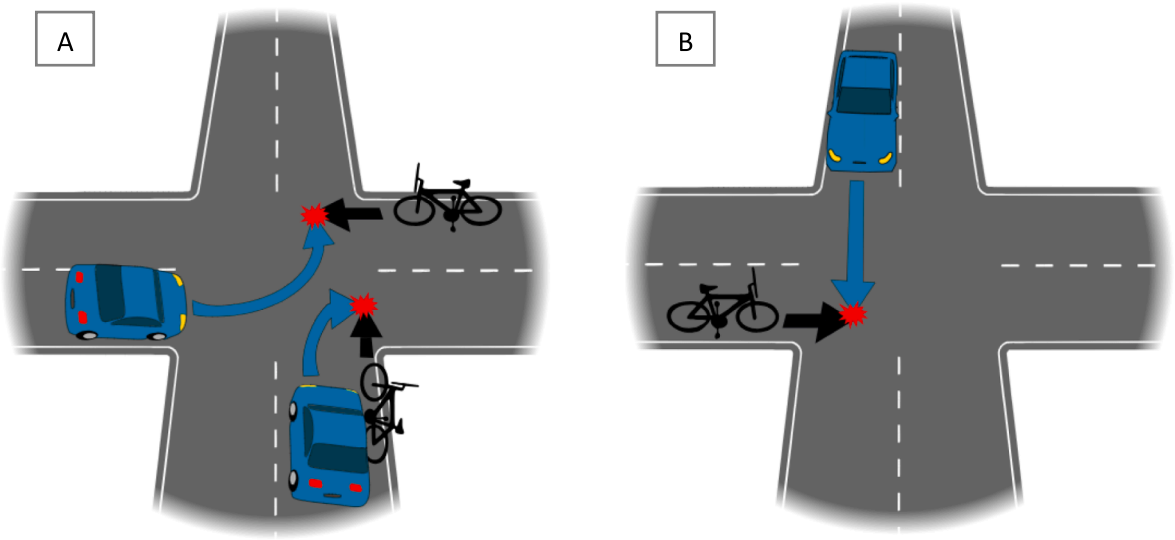

Fig. 2. Most common maneuvers leading to side-on-head collisions (The side of bicycle/PMD impacts the front of the other vehicle). A. Only the other vehicle changes lane or direction; B. No change of lane or direction.

We have investigated several factors influencing injury severity, and have shown that bicycles crashes were more prone to severe injuries (hospitalization and fatalities) compared to PMD crashes when accounting for crash scenario and other adjustment factors; and that the electric mode for these vehicles increased the risk of severe injury. The risk of severe injury was higher when colliding with a truck but lower when colliding with a motorcycle, another bicycle or PMD, or a pedestrian. This ranking correlates with the ORU average mass (Blaizot et al., 2012; Eluru et al., 2008; Kim et al., 2007). The impacting surface (deformable windshield, bumper, another person…) as well as the ORU speed might also significantly affect the kinetics of the collision and the severity of injury (Eluru et al., 2008). One of the main missing adjustment factors for this analysis is the collision speed. Speed is a major factor of road crash severity (Kim et al., 2007) but is difficult to collect accurately and is often missing in observational studies. We hypothesized the ORU real speed to be highly correlated with the road speed limit (which is hence used as a proxy in our analysis), even if it does not necessarily determine it precisely, particularly when the vehicle is turning or reaching an intersection. Another important missing factor is the ownership status of bicycles and PMDs (i.e. whether they are rented or privately owned), as well as the level of experience of riders. Users of rented e-scooters tend to engage in more risky behaviors, such as riding without a helmet, under the influence of alcohol, or with a passenger (Christoforou et al., 2021; Haworth et al., 2021b), which has also been found for cyclists (Haworth et al., 2021b). In addition, they may have less experience in controlling e-scooters, which could increase the risk of injury (Haworth et al., 2021a). In 2021, the majority of e-scooters in Paris and its suburbs were rented (93%) (Christoforou et al., 2021). This is consistent with practices observed in other major cities worldwide (Vienna, Brisbane, Washington, Austin; Cicchino et al., 2023; Haworth et al., 2021b; Laa & Leth, 2020). However, this trend does not apply to all of France, and is likely to evolve locally. A recent report on e-scooters in another French metropolitan area (Lyon) found the opposite (Fiorinotto et al., 2022). Additionally, free-floating e-scooters have been recently banned in cities around the world (Paris, Montreal), which may affect the typology of users and accidents. Our analysis identified several other risk factors known in the literature, including male riders (Eluru et al., 2008), elderly or very young riders (Wang et al., 2015), and riding on slippery, curved, or inclined roads (Boufous et al., 2012; Hosseinpour et al., 2021; Wang et al., 2015). Additionally, we found that riders were more likely to be hospitalized or killed when riding in the dark (Boufous et al., 2012; Eluru et al., 2008), and PMDs were more prone to collisions in the dark compared to bicycles. Encouraging the use of reflector gear usage by riders could enhance visibility, even during daylight hours as suggested by Robartes and Chen (2017).

5. Limitations

The main limitations of this study are the well-known recording bias of police databases, with an underreporting of crashes with minor injuries or no injuries at all, and those involving only one vehicle (such as single falls) (Blaizot et al., 2012; Shinar et al., 2018). The data are thus biased toward the most severe crashes, as well as those involving property damage. The rate of pedestrian crashes is probably underestimated, as vehicle crashes are more likely to be recorded. The number of hospitalized individuals in the French police database is probably also underreported: unless the crash victims do report their hospitalization to the police within 2 months after the accident, they are assumed to be slightly injured. Combining the detailed crash information provided by police databases with epidemiological data from hospitals would be a way to overcome these limitations and provide a more accurate understanding of the overall micromobility crash scene in the future. It should also be noted that not all countries have the same regulations and specificities regarding the use of bicycles and e-scooters (Serra et al., 2021). For example, in France, helmets are not mandatory for PMD riders and cyclists (except those under 12) and riding on sidewalks is prohibited, while e-scooters are allowed on cycle paths with a speed limit of 25 km/h (Serra et al., 2021). The use and ownership of bicycles or PMDs also vary from countries and cities. Therefore, practices vary by location and time, and the conclusions of this study may not be universally applicable.

6. Conclusion

In this study, 16,302 bicycle and 4,118 PMD road collisions were analyzed and compared to identify the most frequent scenarios of collisions against moving vehicles, stationary vehicles, or pedestrians. Side-on-head collisions were the most frequent scenarios for both bicycles or PMDs, and were responsible for over 50% of two-party collisions involving a bicycle or a PMD and a moving vehicle. The prevalent trend

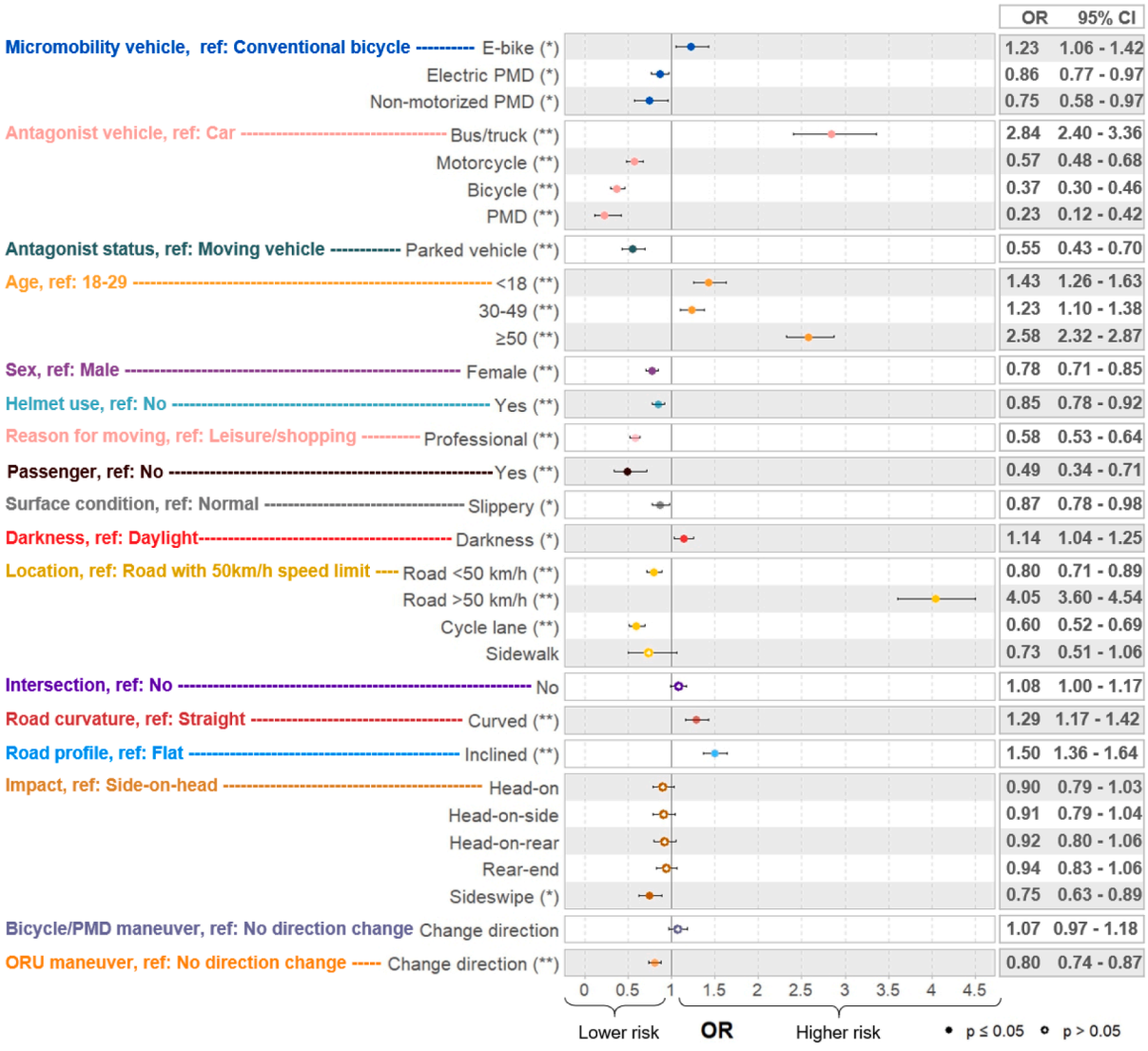

Fig. 3. Multiple logistic regression assessing the effect of road crash parameters on injury severity ("slightly injured or uninjured" vs. "killed or hospitalized"). The dot represents the odds ratio (OR), and the horizontal line the confidence interval (95%CI).The dot is plain when the result is significant ($p \leq 0.05$).* $p \leq 0.05$; ** $p \leq 0.001$. ORU=Other road user (vehicle). The reference categories are indicated on the left, after the variable names. Definition of the impact zones: bicycle/PMD –on- ORU.

was that the bicycles and PMDs did not change direction. The most common ORUs were cars, which accounted for three out of four collisions. We found a greater risk of severe injuries in bicycle collisions compared to PMD collisions, when accounting for collision scenario, road speed limit, and for other adjustment factors. Moreover, several differences in rider characteristics, crash location, and road type were observed between the bicycle and PMD groups, suggesting that these two modes of transportation should not be equated in crash investigations. These results could be useful for future studies on crash reconstruction to better understand the relationship between crash scenarios, human body impact conditions, and risk of injury as well as to evaluate the effectiveness of protective devices for cyclists and PMD users.

Declaration of the use of AI-assisted technologies

During the preparation of this work the authors used ChatGPT version 3.5 (OpenAI) and DeepL Write (DeepL GmbH) in order to improve readability and language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Marianne Guesneau: Conceptualization, Methodology, Visualization, Writing – original draft, Investigation, Writing – review & editing. **Oscar Cherta-Ballester:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Lydiane Agier:** Methodology, Writing – review & editing, Investigation. **Pierre-Jean Arnoux:** Funding acquisition, Supervision, Writing – review & editing. **Wei Wei:** Investigation, Methodology, Writing – review & editing. **Céline Vernet:** Investigation, Methodology, Writing – review & editing. **Valentin Honoré:** Funding acquisition, Writing – review & editing. **Nicolas Bailly:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsr.2024.08.012.

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