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Risk Factors for Overtaking, Rear-End, and Door Crashes Involving Bicycles in the United Kingdom: Revisited and Reanalysed

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Full Title:	Risk Factors for Overtaking, Rear-End, and Door Crashes Involving Bicycles in the United Kingdom: Revisited and Reanalysed
Short Title:	Risk Factors for Overtaking, Rear-End, and Door Crashes Involving Bicycles in the United Kingdom
Corresponding Author:	Chih-Wei Pai Taipei Medical University Taipei, TAIWAN
Keywords:	Bicycle crash; Road segment; Overtaking crash; Rear-end crash; Door crash
Abstract:	<p>Objectives</p> <p>Relevant research has provided valuable insights into risk factors for bicycle crashes at intersections. However, few studies have focused explicitly on three common types of bicycle crashes on road segments: overtaking, rear-end, and door crashes. This study aims to identify risk factors for overtaking, rear-end, and door crashes that occur on road segment.</p> <p>Material and methods</p> <p>We analysed British STATS19 accident records from 1991 to 2020. Using multivariate logistic regression models, we estimated adjusted odds ratios (AORs) with 95% confidence intervals (CIs) for multiple risk factors. The analysis included 127,637 bicycle crashes, categorised into 18,350 overtaking, 44,962 rear-end, 6,363 door, and 57,962 other crashes. overtaking, 44,962 rear-end, 6,363 door, and 57,962 other crashes.</p> <p>Results</p> <p>Significant risk factors for overtaking crashes included speed limits of ≥ 40 miles per hour (mph) (AOR = 2.238, 95% CI = 2.159–2.320), heavy goods vehicles (HGVs) as crash partners (AOR = 2.867, 95% CI = 2.473–3.323), and elderly crash partners (AOR = 2.013, 95% CI = 1.937–2.092). For rear-end crashes, noteworthy risk factors included unlit darkness (AOR = 1.486, 95% CI = 1.404–1.573) and midnight hours (AOR = 1.269, 95% CI = 1.190–1.354). Factors associated with door crashes included speed limits of 20–30 mph (AOR = 16.185, 95% CI = 13.514–19.382) and taxi and private hire cars (AOR = 2.695, 95% CI = 2.310–3.145). Our joint-effect analysis revealed additional interesting results; for example, there were elevated risks for overtaking crashes in rural areas with elderly drivers as crash partners (AOR = 2.93, 95% CI = 2.79–3.08) and with HGVs as crash partners (AOR = 2.62, 95% CI = 2.46–2.78).</p> <p>Conclusions</p> <p>The aforementioned risk factors remained largely unchanged since 2011, when we conducted our previous study. However, the present study concluded that the detrimental effects of certain variables became more pronounced in certain situations. For example, cyclists in rural settings exhibited an elevated risk of overtaking crashes involving HGVs as crash partners.</p>
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Response to Reviewers:

Dear Editors and Reviewers,
 We greatly appreciate the valuable comments and suggestions raised by reviewers. Please very kindly see our responses below, as well as the revised manuscript. We would be glad if you could have our manuscript reviewed again.

Best regards,

Chih-Wei Pai (Prof)
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 Taipei Medical University

Reviewer 2:

1.1 In the Abstract as well as in the results (main text) AOR sometimes expressed with three digits (decimals) and other places two decimals (please consider and use effective digits “decimals”).
 Author’s response: We appreciate the reviewer’s comment and suggestions. All AORs have been amended to two decimals (Please refer to lines 34 to 40 on page 2 in the manuscript).

1.2 In the abstract “results section”: the AOR are sometimes very narrow (please explain).
 Author’s response: We appreciate the reviewer’s comment and question. The narrow confidence intervals (CIs) for the adjusted odds ratios (AORs) indicate high precision in our estimates. This precision is primarily due to our large sample size, which reduces variability and enhances reliability. For example, the AOR for “male as crash partner” in overtaking crashes is 1.28 with a CI of 1.25-1.33, reflecting a strong effect size and

contributing to the narrow CI. Variability and heterogeneity in the data can affect CI width. Risk factors with more consistent effects across the dataset often show narrower CIs (e.g., a).

Katz, M. H. (2011). *Multivariable Analysis: A Practical Guide for Clinicians and Public Health Researchers*.

1.3 In the introduction: word roundabouts are repeated “study demonstrated that roundabout significantly reduces -----“

Author’s response: We appreciate the reviewer’s comment and suggestions. We have revised the manuscript. (Please refer to lines 74 to 76; page 4 in the manuscript): “One study found that roundabouts with dedicated cycle tracks significantly lower the risk of injury for cyclists compared to those without such bicycle infrastructure.”

1.4 In the rationale, the authors still need to emphasize the significance of the three types of crashes, this part of the introduction barely touched this point????

Author’s response: We appreciate the reviewer’s comment and suggestions. We have revised the manuscript. (Please refer to lines 104 to 110; pages 5 -6 in the manuscript): “The high mortality rate from crashes on road segments underscores the significant risks linked to overtaking, rear-end, and door crashes. Overtaking, involving high-speed maneuvers, greatly increases the likelihood of severe accidents. Rear-end crashes, frequently triggered by sudden stops or aggressive tailgating, pose a persistent threat to cyclists. Furthermore, injuries sustained by cyclists striking an opening car door can be devastating due to the impacts from the door, ground, or vehicles behind. These critical issues highlight the urgent need for identifying risk factors for these crashes.”

Statistical analysis:

1.5 - Rationale for considering p value of 0.2 at the univariate (bivariate) level to be incorporated in the multiple Logistic regression models???

Author’s response: We appreciate the reviewer’s comment and question. In the first and second round of review, this reviewer expressed concerns over our use of Chi-square tests to examine the relationship between three crash types and the independent variables. We have now opted to estimate the crude odds ratio by univariate logistic regressions. Please kindly see Table 4 lines 259 to 260; page 15 in the manuscript.

1.6- How the data were handled statistically: descriptive and inferential methods should be mentioned in this section

Author’s response: We appreciate the reviewer’s comment and question. In response to your comment, we have revised the section on statistical handling to provide a more comprehensive explanation of both the descriptive and inferential methods employed. (Please refer to lines 182 to 191; page 9 in the manuscript).

“We initially utilized descriptive statistics to examine the distribution of crash types across various variables such as lighting conditions, speed limit, time of day, and day of the week. Demographic details concerning cyclist casualties encompassed age and sex, while information about the crash partner included vehicle type, age, and sex. This preliminary analysis provided a general picture of basic characteristics of the data and identification of potential patterns. For inferential analysis, we applied the Chi-squared test to investigate associations between crash type and various factors, including cyclist and motorist characteristics, vehicle features, roadway conditions, and temporal variables. We then estimated crude odds ratios by estimating univariate logistic regression and adjusted odds ratios by multivariate logistic models, respectively.”

1.8- What type of model was used (stepwise, or else), how the model was tested to be fit???

Author’s response: We appreciate the reviewer’s comment and question. We used multivariate logistic regression with backward selection to compute adjusted odds ratios (AORs). This method involves initially including all potential predictors and then iteratively removing the least significant variables based on their p-values. In terms of model fit statistics, the final models were chosen based on the p2 statistics (e.g., b). The p2 statistics for the estimated models range from 0.327 to 0.398, indicating a reasonable model fit.

Ben-Akiva, M. E., & Lerman, S. R. (1985). Discrete choice analysis: theory and application to travel demand (Vol. 9). MIT press.

1.9- How the variables were categorized to be suitable for the inclusion of logistic regression analysis?

Author's response: We appreciate the reviewer's comment and question. Considering findings from past studies and selecting the model with the most parsimonious and robust statistical properties (e.g., goodness of fit, reasonable parameter magnitudes, and t-statistics), the variables were categorized and explained as follows:

First, age data were divided into four categories: ≤ 18 (not of legal driving age), 19–40, 41–64, and ≥ 65 (defined as older age by WHO standards). This classification highlights the different risk profiles associated with each age group.

The variable "time of crash" was classified into four periods—midnight (00:00–06:00), rush hours (07:00–08:00 and 17:00–18:00), non-rush hours (09:00–16:00), and evening (19:00–23:00)—to account for fluctuations in traffic patterns and accident likelihood throughout the day.

Speed limits were categorized by location into two types: nonbuilt-up areas (rural, ≥ 40 mph) and built-up areas (urban, 20–30 mph).

Day of the week was grouped as either weekday or weekend to evaluate variations in crash patterns.

These classifications have been commonly adopted in safety literature (e.g., c; d).

Widodo, Akhmad Fajri, et al. "Walking against traffic and pedestrian injuries in the United Kingdom: new insights." *BMC public health* 23.1 (2023): 2205.

Wiratama, Bayu Satria, et al. "Joint effect of heavy vehicles and diminished light conditions on paediatric pedestrian injuries in backover crashes: a UK population-based study." *International journal of environmental research and public health* 19.18 (2022): 11689.

110- The reference group in the multivariate regression table is not consistent along the three types of crashes??? Please explain.

Author's response: We appreciate the reviewer's comment and question. The reference groups in the univariate and multivariate analysis have been assigned consistent. Please kindly see Table 4 lines 259 to 260; pages 14-15 and Table 5 lines 292 to 293; pages 16-17 in the manuscript.

1.11- Joint sensitivity analysis should be mentioned in this section "indication, methods and output"

Author's response: We appreciate the reviewer's insightful comments and suggestions. To illustrate the effectiveness of models with joint effects, we found that these models produced a higher log-likelihood at convergence and demonstrated an improved overall fit, as indicated by a better p^2 statistic.

Moreover, we performed a likelihood ratio test (e.g., e) to confirm the superiority of the joint effects models over the general models. The test statistic is given by:

$$\chi^2 = -2[LL(\beta_G) - LL(\beta_J)]$$

Where $LL(\beta_G)$ represents the log-likelihood at convergence for the general model, and $LL(\beta_J)$ is for the joint effects model. This statistic follows a χ^2 distribution, with degrees of freedom equal to the difference in the number of parameters between the general and joint effects models.

Vuong, Q.H., 1989. Likelihood ratio tests for model selection and non-nested hypothesis. *Econometrica* 57, 307-333.

Results:

1.12- The previous comments on using the Chi-square test remained the same??? Non-specific, non-parametric test and can't point out to the direction of significance???

Author's response: We appreciate this reviewer's comment. In addition to the multivariate logistic regression, we have now estimated the univariate logistic regression models. Please kindly see Table 4 lines 259 to 260; pages 14-15 and Table 5 lines 292 to 293; pages 16-17 in the manuscript.

1.13- What software used to produce figure 2???

Author's response: We appreciate the reviewer's comment and question. We recreated the figure from the previous article (e.g., f) using Photoshop and then edited it in

PowerPoint.

Pai C-W. Overtaking, rear-end, and door crashes involving bicycles: an empirical investigation. *Accid Anal Prev.* 2011;43(3):1228-35.

Review 4

4.1 This has been addressed but in the main document start with background under the background sentences, conclude it with the objective, instead of presenting it as a separate paragraph.

Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (please refer to lines 23 to 27 ; page 2 in the manuscript):
"Background and Objective: Relevant research has provided valuable insights into risk factors for bicycle crashes at intersections. However, few studies have focused explicitly on three common types of bicycle crashes on road segments: overtaking, rear-end, and door crashes. This study aims to identify risk factors for overtaking, rear-end, and door crashes that occur on road segments."

4.2 I understand this response; however, you need to conduct a normality check for all continuous variables like age and others like distance. This helps you to present either the mean age or the median age

Author's response: We appreciate the reviewer's comment and suggestions. Normality check for continuous variables is needed only while estimating a linear regression model. In our study, we estimated several logistic models in which testing for normality and homoscedasticity is not needed. For a comprehensive discussion on the derivation of logistic regression models, see Hosmer et al. (e.g., g).

g. Hosmer Jr, David W., Stanley Lemeshow, and Rodney X. Sturdivant. *Applied logistic regression.* John Wiley & Sons, 2013.

4.3 N(%) consider using this type of reforestation and removed the percentage signs from the table

Author's response: We appreciate the reviewer's comment and suggestions. We have removed the percentage signs and replaced them with "n (%)" in the tables 1, 2 and 3. (Please refer to lines 221-222 of page 11; lines 237 -238 of pages 12- 13; lines 254-255 of pages 13- 14 in the manuscript).

4.4 Data analysed should replace this, you didn't collect data

Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (Please refer to lines 160; page 8 in the manuscript):
"Data analysis"

4.5 I insist this be removed, but keep the proportion there and take this up and say N(%) or read other publication to see how this is presented

Author's response: We appreciate the reviewer's comment and suggestions. We have removed the percentage signs and replaced them with "n (%)" in the table1, 2 and 3. Please refer to lines 221-222 of page 11; lines 237 -238 of pages 12- 13; lines 254-255 of pages 13- 14 in the manuscript.

4.6 This has not been fully addressed. What the authors did was just introduced the corresponding Odds Ratios and P-Values but no result interpretation. Consider doing something like this, "having a HGVs as crash partners had 2.9 times higher likelihood of being involved in overtaking crash", something like this for all the significant variables.

Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (Please refer to 293 to 295; page 17 in the manuscript):

"In overtaking crashes, the presence of heavy goods vehicles (HGVs) as partners increases the likelihood by 1.3 times (AOR = 1.30, 95% CI = 1.27-1.33; p < 0.001)."

4.7 This has now been introduced, however, start with what you found, then bring the reason supporting those findings and lastly place it in the context of other study and cite it.

Author's response: We appreciate the reviewer's comment and suggestions. We have outlined the reasons supporting these findings and, finally, situated them within the context of existing research, providing appropriate citations. (Please refer to lines 344 to 347; pages 19-20 in the manuscript):

"Their large blind spots make it difficult for drivers to see cyclists, increasing the likelihood of crashes during overtaking [e.g., c]. Additionally, HGVs are less

	<p>manoeuvrable compared to passenger cars, which reduces their ability to avoid crashes if cyclists suddenly enter their path [e.g., d]. The speed and distance perception issues between HGVs and cyclists further complicate the judgment of safe overtaking gaps[e.g., e].”</p> <p>c. Marshall, Russell, and Stephen Summerskill. "An objective methodology for blind spot analysis of HGVs using a DHM approach." DS 87-8 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 8: Human Behaviour in Design, Vancouver, Canada, 21-25.08. 2017. 2017.</p> <p>d. Frings, Daniel, Andy Rose, and Anne M. Ridley. "Bicyclist fatalities involving heavy goods vehicles: Gender differences in risk perception, behavioral choices, and training." Traffic injury prevention 13.5 (2012): 493-498.</p> <p>e. Chew, Esther Li-Wen, and Amanda Stephens. "Human Factors That Impact HGV Drivers From Being Aware of VRUs Through Direct and Indirect Vision Mechanisms." 4.8 I think you need to reference this in the method section also where you discussed the data source. Some readers don't reach here</p> <p>Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (please refer to 135 to 137; page 7 in the manuscript): "The data that support the findings of this study are openly available at https://figshare.com/ndownloader/files/48173452."</p>
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<p>Please add funding details. as follow-up to "Financial Disclosure</p>	<p>This study received financial support from the Ministry of Science and Technology, Taiwan (MOST 110–2410-H-038-016-MY2 and MOST 109–2314-B-038-066-); New</p>

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This study was approved by the Joint Institutional Review Board of Taipei Medical University (N202011030). The Joint Institutional Review Board of Taipei Medical University has waived the requirement of informed consent. All methods were performed in accordance with the relevant guidelines and regulations of the Declaration of Helsinki.

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This study utilised the British STATS19 database, which contains data on all road traffic accidents in the United Kingdom. The data that support the findings of this study are openly available at <https://figshare.com/ndownloader/files/48173452>.

<p><i>and contact information or URL).</i></p> <ul style="list-style-type: none">• This text is appropriate if the data are owned by a third party and authors do not have permission to share the data. <p>* typeset</p>	
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34 **Results**

35 Significant risk factors for overtaking crashes included speed limits of ≥ 40 miles per hour (mph)
36 (AOR = 2.238, 95% CI = 2.159–2.320), heavy goods vehicles (HGVs) as crash partners (AOR = 2.867,
37 95% CI 2.473–3.323), and elderly crash partners (AOR = 2.013, 95% CI = 1.937–2.092). For rear-
38 end crashes, noteworthy risk factors included unlit darkness (AOR = 1.486, 95% CI = 1.404–1.573)
39 and midnight hours (AOR = 1.269, 95% CI = 1.190–1.354). Factors associated with door crashes
40 included speed limits of 20–30 mph (AOR = 16.185, 95% CI = 13.514–19.382) and taxi and private
41 hire cars (AOR = 2.695, 95% CI = 2.310–3.145). Our joint-effect analysis revealed additional
42 interesting results; for example, there were elevated risks for overtaking crashes in rural areas
43 with elderly drivers as crash partners (AOR = 2.93, 95% CI = 2.79–3.08) and with HGVs as crash
44 partners (AOR = 2.62, 95% CI = 2.46–2.78).

45

46 **Conclusions**

47 The aforementioned risk factors remained largely unchanged since 2011, when we conducted
48 our previous study. However, the present study concluded that the detrimental effects of certain
49 variables became more pronounced in certain situations. For example, cyclists in rural settings
50 exhibited an elevated risk of overtaking crashes involving HGVs as crash partners.

51

52 **Keywords:** Bicycle crash; Road segment; Overtaking crash; Rear-end crash; Door crash

53

54 **Introduction**

55 In recent years, urban bicycling has become increasingly popular in many countries, offering

56 benefits such as reduced traffic congestion, diminished parking pressure, and a reduction in
57 greenhouse gas emissions [1, 2]. The World Health Organization has highlighted numerous health
58 advantages of moderate-intensity physical activities such as bicycling, including improvements in
59 life expectancy, quality of life, cognitive function, mental health, sleep quality, muscular and
60 cardiorespiratory fitness, and bone and functional health [2].

61 However, despite such health benefits, the risk of injury remains a considerable safety
62 concern for cyclists, who are regarded as vulnerable road users [2, 3]. Traffic crash data indicate
63 that the risk of accidents for cyclists, measured per distance travelled, is approximately 20 times
64 higher than that for vehicle drivers [2]. To address this problem, researchers in the United States
65 developed a comprehensive bicycle route safety rating model with a focus on injury severity [4].
66 This model evaluates multiple operational and physical aspects such as traffic volume, population
67 density, highway classification, lane width, and the presence of one-way streets. In addition, it is
68 capable of predicting the severity of injuries due to motor vehicle–related crashes at specific
69 locations [4]. Another finding was that a route is considered adequately safe if it includes
70 geometric factors that enhance safety [4]. This model can aid urban planners and public officials
71 in creating infrastructure such as bike lanes and implementing strict lane policies to improve
72 cyclist safety [4]. Implementing bike lanes has been demonstrated to reduce crash rates by up to
73 40% among adult cyclists [5]. One study regarding roundabouts indicated that roundabouts with
74 cycle tracks significantly reduced injury risk for cyclists compared with those lacking bicycle
75 infrastructure [6]. Furthermore, adequate night-time lighting on rural roads has the potential to
76 prevent over half of all cyclist injuries [7].

77 Although intersectional crashes are generally more frequent than nonintersectional ones, in

78 2020, 64% of fatal crashes involving cyclists occurred on road segments, defined as areas 20 m
79 away from intersections, whereas only 26% of such fatalities occurred at intersections [8]. Bil et
80 al. demonstrated that car drivers, when at fault for crashes, often cause more serious
81 consequences for cyclists on straight road sections [9]. In crashes occurring on road segments,
82 several factors contribute to high injury severity, including being in a rural region with an elevated
83 speed limit, male gender, and cyclist age of >55 years [10]. Another identified risk factor is
84 bicycling on roads against oncoming traffic [11].

85 Although relevant research has shed light on risk factors for bicycle crashes at intersections,
86 few studies have explicitly investigated crashes on road segments. Studies that have examined
87 bicycle crashes relatively broadly, without distinguishing crash types, have identified several key
88 factors—including vehicle volume [13], traffic density [12], number of lanes [12], access points
89 along road segments [13], shoulder and median widths [13], parking space availability [12, 13],
90 length of continuous two-way left-turn lanes [13], and pavement type [14]—all of which
91 contribute to crashes on road segments. Several studies have specifically explored overtaking,
92 rear-end, and door crashes involving bicycles. A pioneering contribution in this area was made
93 by Pai, who focused on these three types of crashes on road segments [15]. Specifically, Pai
94 identified buses and coaches as common crash partners in overtaking crashes; poor visibility,
95 traversing manoeuvres, and teenage cyclists as risk factors for rear-end crashes; and built-up
96 areas as a risk factor for door crashes [15]. In addition, another study linked the speed of a passing
97 vehicle to increased severity of cyclist injury in overtaking crashes [16].

98 The primary objective of the present study, an extension of our previous study [15], was to
99 analyse police-reported crash data from additional years to determine whether the risk factors

100 for these three crash types remained unchanged. Furthermore, we aimed to untangle the joint
101 associations of several factors—including light conditions, urban versus rural settings, vehicle
102 types, and rider and driver characteristics—with these three crash types.

103

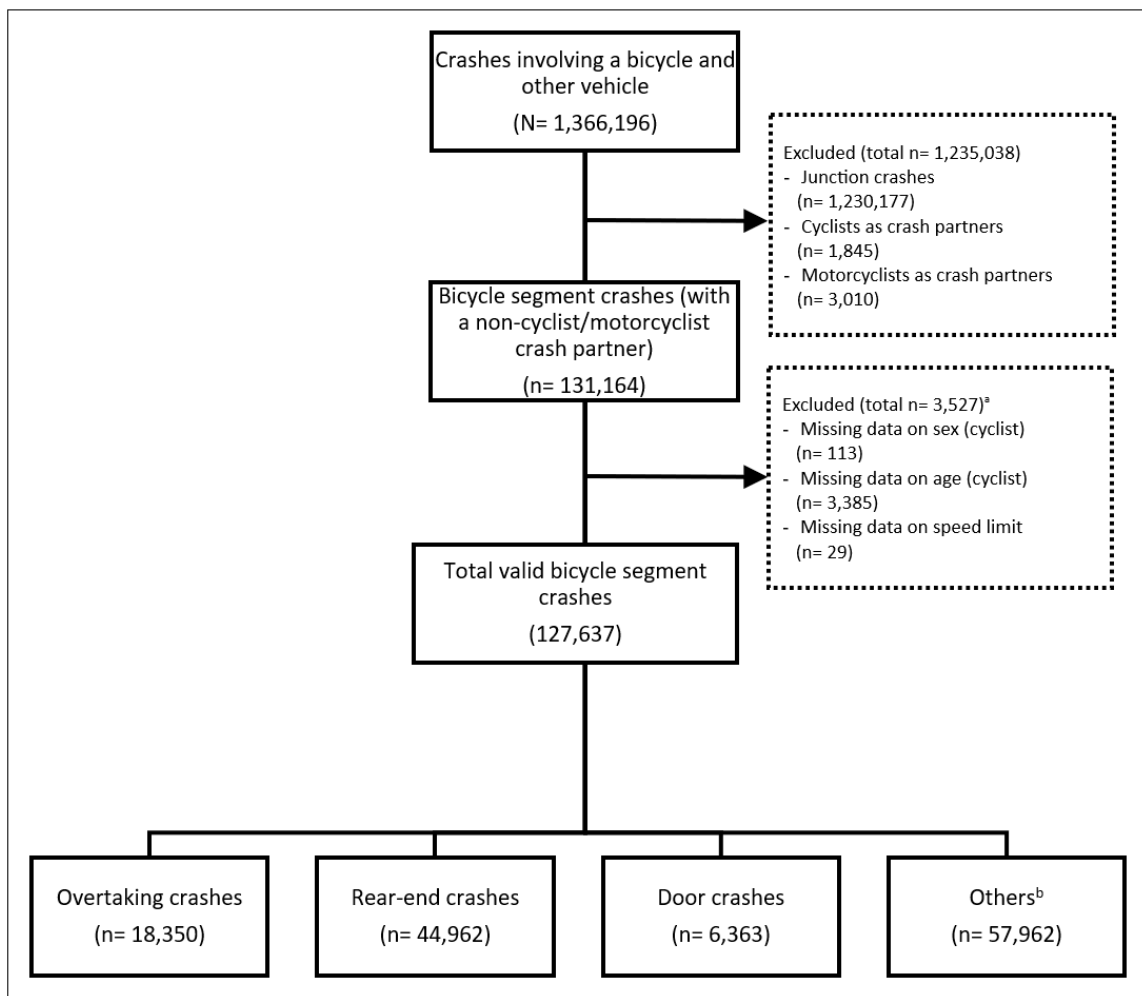
104 **Material and Methods**

105 **Crash data source**

106 The present investigation utilised data from 01/01/1991 to 31/12/2020, obtained from the
107 United Kingdom’s official road traffic casualty database, STATS19. Police record such data either
108 at crash scenes or within 30 days of each crash. The UK’s Department for Transport compiles the
109 data, which the United Kingdom Data Archive then maintains and distributes. The dataset
110 encompasses a variety of variables, including crash circumstances (e.g., time and date, weather
111 conditions, road and light conditions, posted speed limit, road type), vehicle and driver
112 characteristics, demographic details of the drivers, precrash manoeuvres of the vehicles, and the
113 initial impact point of the vehicle. Additionally, the dataset contains demographic information
114 and details regarding injury severity for each casualty. This study adhered to the STROBE
115 (strengthening the reporting of observational studies in epidemiology) reporting guidelines.

116 Injury severity in the aforementioned dataset is divided into three categories, namely slight,
117 serious, and fatal. Fatal injuries refer to those leading to death within 30 days of the accident.
118 Serious injuries include conditions such as fractures, internal injuries, severe cuts and lacerations,
119 concussions, and any injury requiring hospitalisation. Slight injuries include sprains, bruises, and
120 minor cuts, as well as mild shock requiring roadside attention. The exclusive focus of this study
121 was crashes leading to cyclist casualties.

122 As shown in Figure 1, this study analysed 1,366,196 crashes involving bicycles and other
 123 vehicles. Initially, 1,235,032 junction cases were excluded. From the remaining 131,164 bicycle
 124 segment crashes, 3,527 were further excluded because of incomplete demographic data for the
 125 cyclist and missing speed limit information, leaving a valid cohort of 127,637 bicycle segment
 126 crashes for analysis. Within this cohort, this study identified 18,350 overtaking crashes, 44,962
 127 rear-end crashes, 6,363 door crashes, and 57,962 other types of crashes.



128
 129 **Fig. 1.** Flowchart of the study sample selection process. ^aListed excluded criteria are nonexclusive; thus, the sum of
 130 the total may exceed 3,527. ^bOther crashes include reversing crashes and head-on crashes.

131
 132 **Classification of crash types**

133 An overtaking crash is defined as a crash where a motorised vehicle overtakes and collides with

134 a bicycle, which may be travelling straight, overtaking another vehicle, changing lanes, or turning.
135 A rear-end crash occurs when a following vehicle collides with the rear of a bicycle. A door crash
136 involves a bicycle either being struck by or striking the opening door of an automobile. These
137 three crash types were described using schematics in our previous study [15].

138

139 **Data collection**

140 For the present study, the three crash types of focus (overtaking, rear-end, and door crashes)
141 were the binary-dependent variables. The collected data encompassed the following factors:
142 lighting conditions on the roadway at the time of the crash (daylight, darkness-lit, darkness-unlit),
143 the speed limit at the crash scene (rural: ≥ 40 miles per hour [mph]; urban: 20–30 mph), the time
144 of day categorised into four periods according to traffic volume (midnight: 00:00–06:00; rush
145 hours: 07:00–08:00 and 17:00–18:00; nonrush hours: 09:00–16:00; and evening: 19:00–23:00),
146 and the day of the week (weekday or weekend day). The demographic details of cyclist casualties
147 encompassed age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex (male or female). Finally, the
148 demographic details of the crash partner included the type of vehicle (identified as a taxi, private
149 hire car, car, bus, or heavy goods vehicle [HGV]), age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex
150 (male or female).

151

152 **Statistical analysis**

153 This study employed the chi-squared test to examine the associations between crash type and
154 other factors, including cyclist or motorist characteristics, vehicle features, roadway conditions,
155 and temporal variables. Variables with a p value lower than 0.2 in the univariate analysis were

156 subsequently incorporated into the multivariate logistic regression analysis [17]. All statistical
 157 analyses were conducted using SPSS Statistics version 25 for Windows (IBM Corp., Armonk, New
 158 York, USA). A *p* value lower than 0.05 in two-tailed tests was considered statistically significant.

159

160 Results

161 Population characteristics

162 Tables 1, 2, and 3 present the distributions of overtaking, rear-end, and door crashes, respectively,
 163 in relation to multiple independent variables. These data revealed that a significant proportion
 164 of bicycle crashes occurred in daylight (82.31%), occurred in urban settings (78.54%), occurred
 165 during nonrush hours (48.34%), occurred on weekdays (77.49%), involved cyclists aged under 18
 166 years (40.11%), and involved male cyclists (81.30%). Additionally, most crashes involved cars as
 167 crash partners (83.57%), and crash partners were predominately aged 19–40 years (38.47%) and
 168 were male (76.35%). Table 1 highlights an overrepresentation in bicycle overtaking crashes for
 169 certain variables, namely unlit darkness (19.50%), rural areas (24.84%), midnight hours (17.71%),
 170 buses or HGVs as crash partners (24.72%), and elderly crash partners (21.47%) and male crash
 171 partners (15.99%). These results were revealed to be statistically significant by the chi-squared
 172 test ($p < 0.01$).

173

174 **Table 1.** Distribution of overtaking crashes according to a set of independent variables

Variable	Total (n=127,637)	Overtaking crashes (n=18,350)	Non-overtaking crashes (n=109,287)	χ^2 test <i>p</i> value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.31%)	15,283 (14.55%)	89,770 (85.45%)	
Darkness-lit	16,543 (12.96%)	1,889 (11.42%)	14,654 (88.58%)	
Darkness-unlit	6,041 (4.73%)	1,178 (19.50%)	4,863 (80.50%)	

Table 1. Distribution of overtaking crashes according to a set of independent variables (*continued*)

Variable	Total (n=127,637)	Overtaking crashes (n=18,350)	Non-overtaking crashes (n=109,287)	χ^2 test p value
Speed limit, n (%)				<0.001
Rural (\geq 40 mph)	27,395 (21.46%)	6,805 (24.84%)	20,590 (75.61%)	
Urban (20–30 mph)	100,242 (78.54%)	11,545 (11.52%)	88,697 (88.48%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.77%)	852 (17.71%)	3,958 (82.29%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.61%)	5,685 (13.66%)	35,934 (86.34%)	
Nonrush hours (09:00–16:00)	61,696 (48.34%)	9,386 (15.21%)	52,310 (84.79%)	
Evening (19:00–23:00)	19,512 (15.29%)	2,427 (12.44%)	17,085 (87.56%)	
Crash day, n (%)				0.094
Weekend	28,730 (22.51%)	4,218 (14.68%)	24,512 (85.21%)	
Weekday	98,907 (77.49%)	14,132 (14.29%)	84,775 (85.71%)	
Cyclist's age (years), n (%)				<0.001
\leq 18	51,193 (40.11%)	5,220 (10.20%)	45,973 (89.80%)	
19–40	45,760 (35.85%)	7,108 (15.53%)	38,652 (84.47%)	
41–64	26,052 (20.41%)	5,012 (19.24%)	21,040 (80.76%)	
\geq 65	4,632 (3.63%)	1,010 (21.80%)	3,622 (78.20%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.30%)	14,746 (14.21%)	89,020 (85.79%)	
Female	23,871 (18.70%)	3,604 (15.10%)	20,267 (84.90%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.03%)	208 (8.04%)	2,380 (91.96%)	
Car	106,668 (83.57%)	13,599 (12.75%)	93,069 (87.25%)	
Bus/Heavy goods vehicle	18,381 (14.40%)	4,543 (24.72%)	13,838 (75.28%)	
Crash partner's age (years), n (%)				<0.001
\leq 18	2,415 (1.89%)	281 (11.64%)	2,134 (88.36%)	
19–40	49,103 (38.47%)	5,398 (10.99%)	43,705 (89.01%)	
41–64	35,598 (27.89%)	3,973 (11.16%)	31,625 (88.84%)	
\geq 65	40,521 (31.75%)	8,698 (21.47%)	31,823 (78.53%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.35)	15,584 (15.99%)	81,863 (84.01%)	
Female	30,190 (23.765%)	2,766 (9.16%)	27,424 (90.84%)	

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As reported in Table 2, several variables, for instance, unlit darkness (50.19%), rural areas (43.03%), in midnight hours (47.59%), taxis as crash partners (42.35%), and elderly (39.67%) or male crash partners (36.77%) appeared to be disproportionately represented in bicycle rear-end crashes. These results were also revealed to be statistically significant by the chi-squared test ($p < 0.01$).

Table 2. Distribution of rear-end crashes according to a set of independent variables

Variable	Total (n=127,637)	Rear-end crashes (n=44,962)	Non-rear-end crashes (n=82,675)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.31%)	35,726 (34.10%)	69,333 (66.00%)	
Darkness-lit	16,543 (12.96%)	6,204 (37.50%)	10,339 (63.50%)	
Darkness-unlit	6,041 (4.73%)	3,032 (50.19%)	3,003 (49.71%)	

Table 2. Distribution of rear-end crashes according to a set of independent variables (*continued*)

Variable	Total (n=127,637)	Rear-end crashes (n=44,962)	Non-rear-end crashes (n=82,675)	χ^2 test <i>p</i> value
Speed limit, n (%)				<0.001
Rural (\geq 40 mph)	27,395 (21.46%)	11,788 (43.03%)	15,607 (56.97%)	
Urban (20–30 mph)	100,242 (78.54%)	33,174 (33.09%)	67,068 (66.91%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.77%)	2,289 (47.59%)	2,521 (52.41%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.61%)	15,089 (36.26%)	26,530 (63.74%)	
Nonrush hours (09:00–16:00)	61,696 (48.34%)	20,723 (33.59%)	40,973 (66.41%)	
Evening (19:00–23:00)	19,512 (15.29%)	6,861 (36.16%)	12,651 (64.85%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.51%)	9,485 (33.01%)	19,245 (66.99%)	
Weekday	98,907 (77.49%)	35,477 (35.87%)	63,430 (64.13%)	
Cyclist's age (years), n (%)				<0.001
\leq 18	51,193 (40.11%)	13,446 (26.27%)	37,747 (73.73%)	
19–40	45,760 (35.85%)	19,102 (41.74%)	26,658 (58.26%)	
41–64	26,052 (20.41%)	10,619 (40.76%)	15,433 (59.24%)	
\geq 65	4,632 (3.63%)	1,795 (38.75%)	2,837 (61.25%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.30%)	37,175 (35.83%)	66,591 (64.17%)	
Female	23,871 (18.70%)	7,787 (32.62%)	16,084 (67.38%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.03%)	1,096 (42.35%)	1,492 (57.65%)	
Car	106,668 (83.57%)	37,202 (34.88%)	71,342 (66.88%)	
Bus/Heavy goods vehicle	18,381 (14.40%)	6,664 (36.25%)	9,841 (53.54%)	
Crash partner's age (years), n (%)				<0.001
\leq 18	2,415 (1.89%)	870 (36.02%)	1,545 (63.98%)	
19–40	49,103 (38.47%)	16,282 (33.16%)	32,821 (66.84%)	
41–64	35,598 (27.89%)	11,736 (32.97%)	23,862 (67.03%)	
\geq 65	40,521 (31.75%)	16,074 (39.67%)	24,447 (60.33%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.35%)	35,828 (36.77%)	61,619 (63.23%)	
Female	30,190 (23.65%)	9,134 (30.26%)	21,056 (69.74%)	

183

184 Table 3 demonstrates that cyclists in several conditions, such as in unlit darkness (6.23%), in

185 urban areas (6.22%), when they were female (8.21%), when taxi/private hire car were crash

186 partners (10.55%), and when crash partners were female (7.42%), exhibited a higher risk of door

187 crashes. These results were revealed to be statistically significant by the chi-squared test ($p <$

188 0.01).

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193 **Table 3.** Distribution of door crashes according to a set of independent variables

Variable	Total (n=127,637)	Door crashes (n=6,363)	Non-door crashes (n=121,274)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.31%)	5,192 (4.94%)	99,861 (95.06%)	
Darkness-lit	16,543 (12.96%)	1,031 (6.23%)	15,512 (93.77%)	
Darkness-unlit	6,041 (4.73%)	140 (2.32%)	5,901 (97.68%)	
Speed limit, n (%)				<0.001
Rural (\geq 40 mph)	27,395 (21.46%)	123 (0.45%)	27,272 (99.55%)	
Urban (20–30 mph)	100,242 (78.54%)	6,240 (6.22%)	94,002 (93.78%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.77%)	113 (2.35%)	4,697 (97.65%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.61%)	2,056 (4.94%)	39,563 (95.06%)	
Nonrush hours (09:00–16:00)	61,696 (48.34%)	3,363 (5.54%)	58,333 (94.55%)	
Evening (19:00–23:00)	19,512 (15.29%)	831 (4.26%)	18,681 (95.74%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.51%)	1,072 (3.73%)	27,658 (96.27%)	
Weekday	98,907 (77.49%)	5,291 (5.35%)	93,616 (94.65%)	
Cyclist's age (years), n (%)				<0.001
\leq 18	51,193 (40.11%)	802 (1.57%)	50,391 (98.43%)	
19–40	45,760 (35.85%)	3,474 (7.59%)	42,286 (93.41%)	
41–64	26,052 (20.41%)	1,773 (6.81%)	24,279 (93.19%)	
\geq 65	4,632 (3.63%)	314 (6.78%)	4,318 (93.22%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.30%)	4,404 (4.24%)	99,362 (95.76%)	
Female	23,871 (18.70%)	1,959 (8.21%)	21,912 (91.79%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.03%)	273 (10.55%)	2,315 (89.45%)	
Car	106,668 (83.57%)	5,514 (5.17%)	101,154 (94.83%)	
Bus/Heavy goods vehicle	18,381 (14.40%)	576 (3.13%)	17,805 (96.87%)	
Crash partner's age (years), n (%)				<0.001
\leq 18	2,415 (1.89%)	1,62 (5.22%)	2,253 (93.29%)	
19–40	49,103 (38.47%)	2,585 (5.26%)	46,518 (94.74%)	
41–64	35,598 (27.89%)	1,887 (5.30%)	33,711 (94.70%)	
\geq 65	40,521 (31.75%)	1,729 (4.27%)	38,792 (95.73%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.35%)	4,123 (4.23%)	93,324 (95.77%)	
Female	30,190 (23.65%)	2,240 (7.42%)	27,950 (92.58%)	

194

195 **Risk factors for the three crash types**

196 Table 4 presents the logistic regression model results. Regarding overtaking crashes, the
 197 identified risk factors included daylight conditions (adjusted odds ratio [AOR] = 1.233, 95%
 198 confidence interval [CI] = 1.162–1.309), speed limits of \geq 40 mph (AOR = 2.238, 95% CI = 2.159–
 199 2.320), nonrush hours (AOR = 1.091, 95% CI 1.031–1.154), cyclists aged \geq 65 years (AOR = 1.785,

200 95% CI = 1.649–1.931), female cyclists (AOR = 1.106, 95% CI = 1.062–1.153), HGVs as crash
 201 partners (AOR = 2.867, 95% CI = 2.473–3.323), elderly crash partners (AOR = 2.013, 95% CI =
 202 1.937–2.092), and male crash partners (AOR = 1.353, 95% CI = 1.292–1.416).

203 For rear-end crashes, noteworthy risk factors included unlit darkness (AOR = 1.486, 95% CI
 204 = 1.404–1.573), speed limits of ≥ 40 mph (AOR = 1.315, 95% CI = 1.277–1.354), weekdays (AOR =
 205 1.090, 95% CI = 1.059–1.122), midnight hours (AOR = 1.269, 95% CI = 1.190–1.354), and taxis as
 206 crash partners (AOR = 1.286, 95% CI = 1.186–1.394).

207 Regarding door crashes, significant risk factors included lit darkness (AOR = 1.373, 95% CI =
 208 1.141–1.651), speed limits of 20–30 mph (AOR = 16.185, 95% CI = 13.514–19.382), weekdays
 209 (AOR = 1.246, 95% CI = 1.162–1.336), and nonrush hours (AOR = 2.912, 95% CI = 2.384–3.556).
 210 Additionally, female cyclists (AOR = 1.675, 95% CI = 1.582–1.774), taxis or private hire cars as
 211 crash partners (AOR = 2.695, 95% CI = 2.310–3.145), male crash partners (AOR = 1.373, 95% CI =
 212 1.296–1.455), and crash partners aged 41–64 years (AOR = 1.855, 95% CI = 1.625–2.117) were
 213 associated with door crashes.

214

215 **Table 4.** Multivariate logistic regression results

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	<i>p</i> value	AOR (95% CI)	<i>P</i> value	AOR (95% CI)	<i>P</i> value
Light condition						
Daylight	1.233 (1.162, 1.309)	<0.001	Ref		1.146 (0.958, 1.370)	0.137
Darkness-lit	Ref		1.042 (1.002, 1.085)	0.041	1.373 (1.141, 1.651)	0.001
Darkness-unlit	1.152 (1.059, 1.253)	0.001	1.486 (1.404, 1.573)	<0.001	Ref	
Speed limit						
Rural (≥ 40 mph)	2.238 (2.159, 2.320)	<0.001	1.315 (1.277, 1.354)	<0.001	Ref	
Urban (20–30 mph)	Ref		Ref		16.185 (13.514, 19.382)	<0.001
Crash time						
Midnight	1.073 (0.982, 1.173)	0.119	1.269 (1.190, 1.354)	<0.001	Ref	
Rush hours	1.059 (1.002, 1.120)	0.043	1.108 (1.078, 1.139)	<0.001	2.502 (2.051, 3.052)	<0.001
Nonrush hours	1.091 (1.031, 1.154)	0.003	Ref		2.912 (2.384, 3.556)	<0.001
Evening	Ref		0.992 (0.953, 1.032)	0.686	2.014 (1.646, 2.465)	<0.001

Table 4. Multivariate logistic regression results (*continued*)

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	<i>p</i> value	AOR (95% CI)	<i>p</i> value	AOR (95% CI)	<i>p</i> value
Crash day						
Weekend	1.031 (0.991, 1.072)	0.132	Ref		Ref	
Weekday	Ref		1.090 (1.059, 1.122)	<0.001	1.246 (1.162, 1.336)	<0.001
Cyclist's age (years)						
≤18	Ref		Ref		Ref	
19–40	1.292 (1.242, 1.345)	<0.001	1.839 (1.788, 1.891)	<0.001	5.943 (5.489, 6.435)	<0.001
41–64	1.509 (1.444, 1.578)	<0.001	1.731 (1.676, 1.789)	<0.001	6.129 (5.621, 6.684)	<0.001
≥65	1.785 (1.649, 1.931)	<0.001	1.671 (1.568, 1.780)	<0.001	5.988 (5.217, 6.874)	<0.001
Cyclist's sex						
Male	Ref		1.172 (1.137, 1.208)	<0.001	Ref	
Female	1.106 (1.062, 1.153)	<0.001	Ref		1.675 (1.582, 1.774)	<0.001
Crash partner						
Taxi/Private hire car	Ref		1.286 (1.186, 1.394)	<0.001	2.695 (2.310, 3.145)	<0.001
Car	1.571 (1.359, 1.816)	<0.001	Ref		2.089 (1.908, 2.286)	<0.001
Bus/Heavy goods vehicle	2.867 (2.473, 3.323)	<0.001	1.099 (1.061, 1.139)	<0.001	Ref	
Crash partner's age (years)						
≤18	1.097 (0.963, 1.249)	0.162	1.225 (1.188, 1.263)	<0.001	1.507 (1.313, 1.731)	<0.001
19–40	Ref		1.038 (1.008, 1.069)	0.013	1.855 (1.625, 2.117)	<0.001
41–64	0.950 (0.909, 0.994)	0.025	Ref		1.801 (1.574, 2.060)	<0.001
≥65	2.013 (1.937, 2.092)	<0.001	1.241 (1.137, 1.355)	<0.001	Ref	
Crash partner's sex						
Male	1.353 (1.292, 1.416)	<0.001	1.150 (1.117, 1.185)	<0.001	1.373 (1.296, 1.455)	<0.001
Female	Ref		Ref		Ref	

216

217 Figure 2 presents a forest plot demonstrating the joint effects of several variables on the

218 three crash types when other variables were controlled for. An elevated risk of overtaking crashes

219 was evident in rural areas with elderly drivers as crash partners (AOR = 2.93, 95% CI = 2.79–3.08),

220 HGVs as crash partners (AOR = 2.62, 95% CI = 2.46–2.78), and elderly cyclists involved in accidents

221 during weekends (AOR = 1.56, 95% CI = 1.34–1.81). The risk of rear-end crashes was increased by

222 the synergistic interaction of unlit darkness with midnight (AOR = 1.68, 95% CI = 1.48–1.90) and

223 by rural areas (AOR = 2.15, 95% CI = 2.01–2.31). Furthermore, bicycling at midnight in rural areas

224 was associated with an increased risk of rear-end crashes (AOR = 1.68; 95% CI = 1.51–1.86). In

225 urban settings, the risk of door crashes was higher for female cyclists (AOR = 2.29; 95% CI = 2.17–

226 2.43) and for elderly cyclists (AOR = 2.06; 95% CI = 1.82–2.34). Finally, female cyclists exhibited a
 227 112% higher likelihood of door crashes when the crash partner was a taxi (AOR = 2.12; 95% CI =
 228 1.68–2.69).

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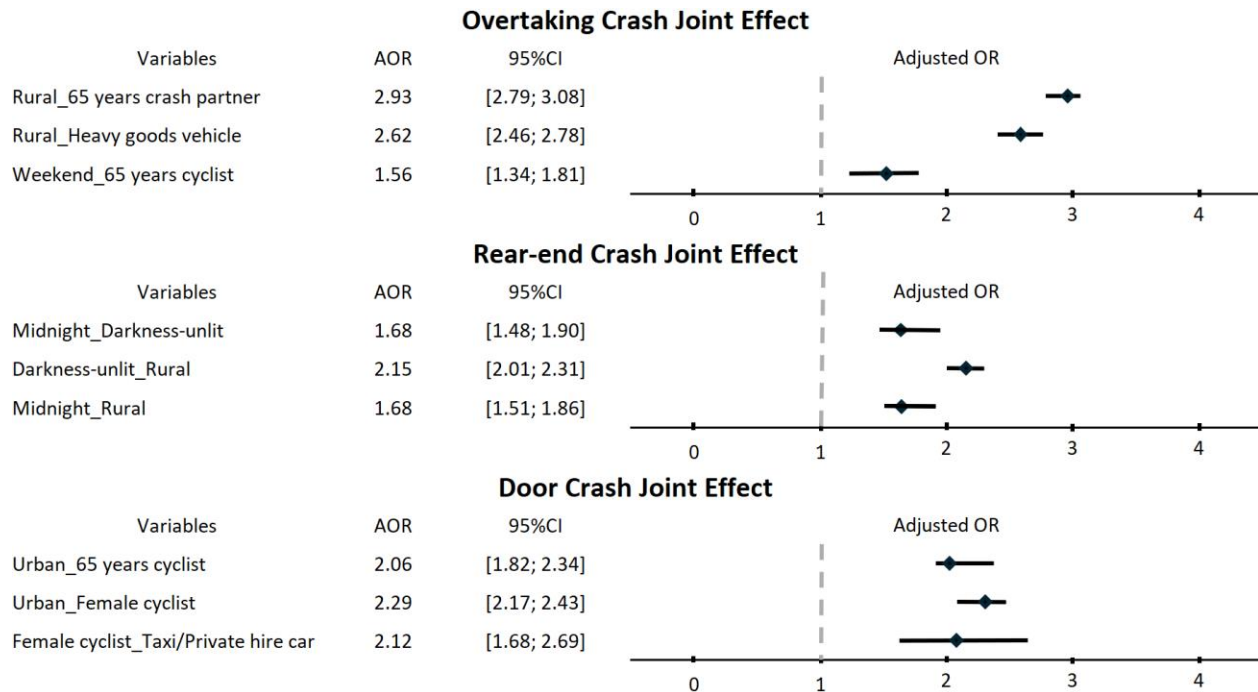


Fig. 2. Joint effects of several variables on the three crash types.

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233 Discussion

234 This study explored the relationships among individual and environmental factors in relation to
 235 three common bicycle crash types (overtaking, rear-end, and door crashes) on roads in the United
 236 Kingdom from 1991 to 2020. The findings revealed several significant factors. First, for overtaking
 237 crashes, HGVs as crash partners, rural areas, and the involvement of elderly crash partners
 238 emerged as key contributing factors. Second, unlit darkness, midnight hours, and rural areas
 239 were the factors most closely associated with rear-end crashes. Third, urban areas and taxis as
 240 crash partners significantly increased the likelihood of door crashes. Moreover, male crash
 241 partners were found to be a consistent risk factor across all three crash types. These findings

242 warrant further discussion and thus are elaborated on in this section of this paper.

243 Our research findings identified specific risk factors for overtaking crashes, namely rural
244 areas, HGVs as crash partners, and elderly crash partners. These findings align with those of a
245 previous study [18], which similarly observed that elderly drivers, driving speeds surpassing 10
246 mph, and the presence of pick-up trucks increased the overtaking crash risk. We further found
247 that the detrimental effect of HGVs on overtaking crashes was more pronounced in rural areas
248 and when the crash partner was elderly. A behavioural study suggested that compared with cars,
249 HGVs tended to maintain a narrower clearance zone when overtaking bicycles [19]. Pai et al. [15]
250 speculated that the time pressures on HGV drivers for timely loading and unloading might lead
251 to reckless driving. Our findings underscore the necessity of implementing measures such as
252 ‘Share the Road’ warning signs [20], particularly in rural settings, where HGVs are likely to execute
253 overtaking manoeuvres at high speed. Such measures could prompt motor vehicles to maintain
254 safer distances from the edges of travel lanes, especially in areas with a notable presence of both
255 HGVs and bicycles.

256 We also identified elderly drivers as a factor contributing to overtaking crashes—a finding
257 consistent with relevant research [18]. As individuals age, their risk of being involved in road
258 accidents is influenced by declines in their cognitive capabilities [21], their health [22], and their
259 driving performance [23]. Notably, crashes involving elderly individuals often occur in scenarios
260 with challenging conditions, including at intersections without traffic control measures, on high-
261 speed roads, during adverse weather conditions, in poorly lit areas, and in head-on accidents
262 [24–26]. The heightened level of risk under such conditions may be attributed to cognitive and
263 perceptual decline in older drivers, which could affect their capacity to execute actions such as

264 overtaking manoeuvres safely. Accordingly, developing specialised cognitive training
265 programmes as interventions to enhance road safety for elderly drivers is evidently necessary
266 [27].

267 In the present study, several factors were found to increase the risk of rear-end crashes on
268 road segments, including darkness with unlit surroundings, midnight hours, and rural settings
269 (speed limit > 40 mph). Although few studies have specifically addressed rear-end crashes
270 involving bicycles on road segments, available data suggest that the low conspicuity of bicycles,
271 especially at night, is a recurrent factor in rear-end crashes [15, 28]. Moreover, a lack of adequate
272 street lighting, which is common in rural settings, predisposes cyclists to rear-end crashes [15].
273 Our joint-effects analysis further indicated that the detrimental effect of unlit darkness is more
274 pronounced in rural areas and during midnight hours. Potential intervention strategies to
275 mitigate rear-end crashes include enhancing illumination and executing speed control
276 management on rural road segments with heavy bicycle traffic.

277 Next, our analysis successfully identified associations of urban areas and taxis and private
278 hire cars as crash partners with door crashes on road segments. Although research specifically
279 focusing on door crashes on road segments is limited, similar findings were documented by Pai,
280 indicating that urban roadways and taxis contributed to door crashes [15]. However, determining
281 the factors influencing this trend poses a challenge. One possible explanation could be the
282 increased presence of taxis or private hire cars in such areas, where passengers often disembark.
283 Additionally, our analysis further revealed an elevated risk of door crashes involving crashes with
284 taxis in urban areas. To reduce door crashes on road segments, educating taxi drivers, as well as
285 passengers, about the importance of vigilance when opening doors near traffic is essential [15].

286 In addition, cyclists should be advised to maintain at least a door's width distance from all parked
287 cars to improve the sight triangles of drivers and increase the visibility of cyclists [29].
288 Implementing a two-stage door opening mechanism for vehicles, which would enable drivers to
289 verify the presence of bicycles to the rear, could also be beneficial [30].

290 This study had several limitations that warrant acknowledgement. First, the substantial
291 underreporting of nonfatal casualties to the police, particularly casualties involving cyclists not
292 obligated to report accidents, is a critical factor to consider. Such underreporting, as highlighted
293 by the U.K. Government's Department for Transport [31], likely results in the incomplete
294 representation of nonfatal and 'slight' casualties in road casualty data. Second, the STATS19 data
295 utilised in this study lack critical variables, including precrash speeds, specific geometric
296 characteristics of roadways, data regarding alcohol and illicit substance use, and cyclist speed at
297 the time of an accident. Moreover, critical exposure data—such as those related to traffic flow,
298 rider or driver experience, and other elements of risk exposure—are absent, and the absence of
299 such details limits our ability to fully account for potential variations resulting from unobserved
300 factors in the analyses. Finally, this study did not explore annual trends in each type of bicycle
301 crash over the 30-year study period; investigating such trends could provide insights regarding
302 changing behaviours among cyclists and motor vehicle drivers as well as the effects of legislative
303 changes for road speed limits.

304

305 **Conclusions**

306 This study identified several significant risk factors for the three predominate types of crashes
307 involving cyclists on road segments: HGVs as crash partners, elderly crash partners, and rural

308 areas for overtaking crashes; unlit darkness, midnight hours, and rural areas for rear-end crashes;
309 and urban areas and taxis as crash partners for door crashes. These risk factors remained
310 unchanged since our previous study conducted in 2011 [15]. The present research enhances the
311 field of bicycle safety research by concluding that the detrimental effects of certain variables
312 become more pronounced under certain conditions. For example, first, cyclists in rural settings
313 exhibited an elevated risk of overtaking crashes involving HGVs. Second, the rear-end crash risk
314 increases in the combined presence of unlit darkness, midnight hours, and rural areas. Finally, in
315 urban settings, the likelihood of door crashes increases when a taxi is the crash partner.

316

317 **Abbreviations**

318 WHO: World Health Organization; HGVs: heavy goods vehicles; AOR: adjusted odds ratio; CI:
319 confidence interval.

320

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323

324 **Author contributions**

325 **Literature review:** Chun-Chieh Chao.

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339 interpretation of data, or preparation of the manuscript.

340

341 **Availability of data and materials**

342 This study utilised the British STATS19 database, which contains data on all road traffic accidents
343 in the United Kingdom. The data that support the findings of this study are openly available at
344 <https://www.data.gov.uk/dataset/cb7ae6f0-4be6-4935-9277-47e5ce24a11f/road-safety-data>.

345

346 **Declarations**

347 **Ethical approval and consent to participate**

348 This study was conducted in accordance with the Declaration of Helsinki and approved by the
349 Joint Institutional Review Board of Taipei Medical University (N202011030).

350

351 **Consent for publication**

352 This study was approved by the Joint Institutional Review Board of Taipei Medical
353 University (N202011030). The Joint Institutional Review Board of Taipei Medical University has
354 waived the requirement of informed consent. All methods were performed in accordance with
355 the relevant guidelines and regulations of the Declaration of Helsinki.

356

357 **Competing interests**

358 The authors declare that they have no competing interests in relation to this work.

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1 **Risk Factors for Overtaking, Rear-End, and Door Crashes Involving Bicycles in the United**
2 **Kingdom: Revisited and Reanalysed**
3

4 **Chun-Chieh Chao^{1,2,3†}, Hon-Ping Ma^{1,3,7}, Li Wei^{1,8,9}, Yen-Nung Lin^{1,10}, Chenyi Chen¹, Wafaa Saleh¹¹, Bayu Satria**
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22 **Abstract**

23 **Background:** Relevant research has provided valuable insights into risk factors for bicycle crashes
24 at intersections. However, few studies have focused explicitly on three common types of bicycle
25 crashes on road segments: overtaking, rear-end, and door crashes.

26 **Objective:** This study aims to identify risk factors for overtaking, rear-end, and door crashes that
27 occur on road segment.

28 **Material and methods**

29 We analysed British STATS19 accident records from 1991 to 2020. Using multivariate logistic
30 regression models, we estimated adjusted odds ratios (AORs) with 95% confidence intervals (CIs)
31 for multiple risk factors. The analysis included 127,637 bicycle crashes, categorised into 18,350
32 overtaking, 44,962 rear-end, 6,363 door, and 57,962 other crashes.

33 **Results**

34 Significant risk factors for overtaking crashes included speed limits of ≥ 40 miles per hour (mph)
35 (AOR = 2.238, 95% CI = 2.159–2.320), heavy goods vehicles (HGVs) as crash partners (AOR = 2.867,
36 95% CI 2.473–3.323), and elderly crash partners (AOR = 2.013, 95% CI = 1.937–2.092). For rear-
37 end crashes, noteworthy risk factors included unlit darkness (AOR = 1.486, 95% CI = 1.404–1.573)
38 and midnight hours (AOR = 1.269, 95% CI = 1.190–1.354). Factors associated with door crashes
39 included speed limits of 20–30 mph (AOR = 16.185, 95% CI = 13.514–19.382) and taxi and private
40 hire cars (AOR = 2.695, 95% CI = 2.310–3.145). Our joint-effect analysis revealed additional
41 interesting results; for example, there were elevated risks for overtaking crashes in rural areas
42 with elderly drivers as crash partners (AOR = 2.93, 95% CI = 2.79–3.08) and with HGVs as crash
43 partners (AOR = 2.62, 95% CI = 2.46–2.78).

44

45 **Conclusions**

46 The aforementioned risk factors remained largely unchanged since 2011, when we conducted
47 our previous study. However, the present study concluded that the detrimental effects of certain
48 variables became more pronounced in certain situations. For example, cyclists in rural settings
49 exhibited an elevated risk of overtaking crashes involving HGVs as crash partners.

50

51 **Keywords:** Bicycle crash; Road segment; Overtaking crash; Rear-end crash; Door crash

52

53

54 **Introduction**

55 In recent years, urban bicycling has become increasingly popular in many countries, offering
56 benefits such as reduced traffic congestion, diminished parking pressure, and a reduction in
57 greenhouse gas emissions [1, 2]. The World Health Organization has highlighted numerous health
58 advantages of moderate-intensity physical activities such as bicycling, including improvements in
59 life expectancy, quality of life, cognitive function, mental health, sleep quality, muscular and
60 cardiorespiratory fitness, and bone and functional health [2].

61 However, despite such health benefits, the risk of injury remains a considerable safety
62 concern for cyclists, who are regarded as vulnerable road users [2, 3]. Traffic crash data indicate
63 that the risk of accidents for cyclists, measured per distance travelled, is approximately 20 times
64 higher than that for vehicle drivers[2]. To address this problem, researchers in the United States
65 developed a comprehensive bicycle route safety rating model with a focus on injury severity [4].

66 This model evaluates multiple operational and physical aspects such as traffic volume, population
67 density, highway classification, lane width, and the presence of one-way streets. In addition, it is
68 capable of predicting the severity of injuries due to motor vehicle–related crashes at specific
69 locations [4]. Another finding was that a route is considered adequately safe if it includes
70 geometric factors that enhance safety [4]. This model can aid urban planners and public officials
71 in creating infrastructure such as bike lanes and implementing strict lane policies to improve
72 cyclist safety [4]. Implementing bike lanes has been demonstrated to reduce crash rates by up to
73 40% among adult cyclists [5]. One study regarding roundabouts indicated that roundabouts with
74 cycle tracks significantly reduced injury risk for cyclists compared with those lacking bicycle
75 infrastructure [6]. Furthermore, adequate night-time lighting on rural roads has the potential to
76 prevent over half of all cyclist injuries [7]. Bicycle crashes can also impose a significant burden on
77 healthcare expenses. Elvik and Sundfør [8] have discussed the economic implications and
78 healthcare expenditures associated with bicycle accidents. For instance, in Belgium, the average
79 cost of bicycle accidents per case is estimated at 841 euros [9]. In the Netherlands, the total
80 annual cost has been reported as €410.7 million [10].

81 Although intersectional crashes are generally more frequent than nonintersectional ones, in
82 2020, 64% of fatal crashes involving cyclists occurred on road segments, defined as areas 20 m
83 away from intersections, whereas only 26% of such fatalities occurred at intersections [11]. Bil et
84 al. demonstrated that car drivers, when at fault for crashes, often cause more serious
85 consequences for cyclists on straight road sections [12]. In crashes occurring on road segments,
86 several factors contribute to high injury severity, including being in a rural region with an elevated
87 speed limit, male gender, and cyclist age of >55 years [13]. Another identified risk factor is

88 bicycling on roads against oncoming traffic [14].

89 Although relevant research has shed light on risk factors for bicycle crashes at intersections,
90 few studies have explicitly investigated crashes on road segments. Bicycle crashes on road
91 segments remain a substantial issue for public health concern. This study aims to fill a critical gap
92 by conducting a thorough examination of the risk factors associated with three distinct bicycle
93 crash types: overtaking, rear-end, and door crashes that occur on road segments. Studies that
94 have examined bicycle crashes relatively broadly, without distinguishing crash types, have
95 identified several key factors—including vehicle volume [15], traffic density [16], number of lanes
96 [16], access points along road segments [15], shoulder and median widths [15], parking space
97 availability [15, 16] , length of continuous two-way left-turn lanes [15], and pavement type [17]—
98 all of which contribute to bicycle crashes on road segments. Two exceptional work have
99 examined risk factors for overtaking, rear-end, and door crashes [18, 19]. Specifically, Pai
100 identified buses and coaches as common crash partners in overtaking crashes, poor visibility,
101 traversing manoeuvres, and teenage cyclists as risk factors for rear-end crashes, and built-up
102 areas as a risk factor for door crashes [18]. In addition, another study linked the speed of a passing
103 vehicle to increased severity of cyclist injury in overtaking crashes [19].

104 The primary objective of the present study, an extension of our previous study [18], was to
105 analyse police-reported crash data from additional years to determine whether the risk factors
106 for these three crash types remained unchanged. The study addresses a critical gap in current
107 research, focusing on crashes specifically occurring on road segments. Existing literature offers
108 limited insights into these crash types, highlighting a crucial need for targeted investigations.
109 These crashes have the potential for severe impacts, involving complex dynamics that demand a

110 nuanced understanding for effective mitigation strategies. By exploring these factors, our
111 research aims to significantly enhance cyclist safety within this particular context. Furthermore,
112 we aimed to untangle the joint associations of several factors—including light conditions, urban
113 versus rural settings, vehicle types, and rider and driver characteristics—with these three crash
114 types.

115

116 **Material and Methods**

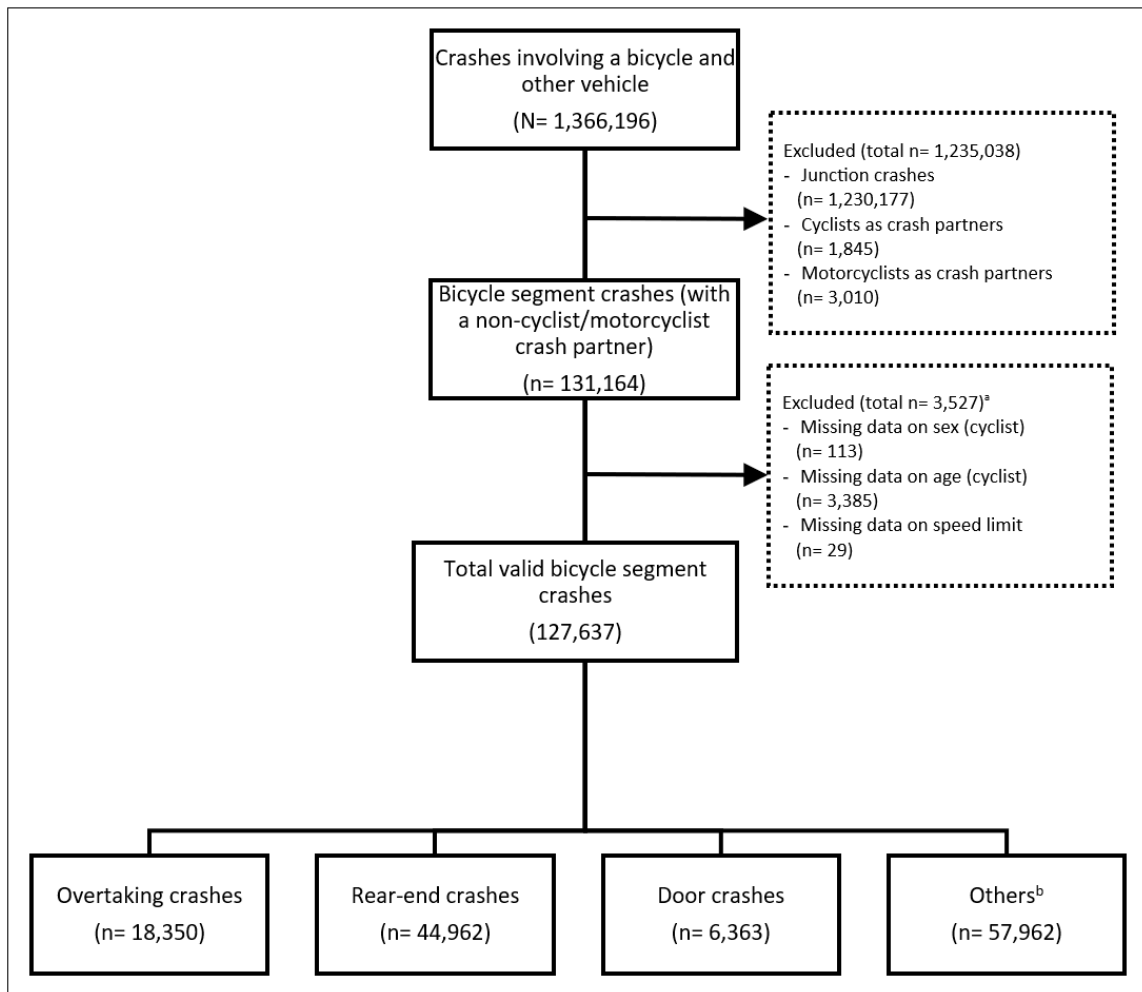
117 **Crash data source**

118 The present investigation utilised data from 01/01/1991 to 31/12/2020, obtained from the
119 United Kingdom’s official road traffic casualty database, STATS19. Police record such data either
120 at crash scenes or within 30 days of each crash. The UK’s Department for Transport compiles the
121 data, which the United Kingdom Data Archive then maintains and distributes. The dataset
122 encompasses a variety of variables, including crash circumstances (e.g., time and date, weather
123 conditions, road and light conditions, posted speed limit, road type), vehicle and driver
124 characteristics, demographic details of the drivers, precrash manoeuvres of the vehicles, and the
125 initial impact point of the vehicle. Additionally, the dataset contains demographic information
126 and details regarding injury severity for each casualty. This study adhered to the STROBE
127 (strengthening the reporting of observational studies in epidemiology) reporting guidelines.[20]

128 Injury severity in the aforementioned dataset is divided into three categories, namely slight,
129 serious, and fatal. Fatal injuries refer to those leading to death within 30 days of the accident.
130 Serious injuries include conditions such as fractures, internal injuries, severe cuts and lacerations,
131 concussions, and any injury requiring hospitalisation. Slight injuries include sprains, bruises, and

132 minor cuts, as well as mild shock requiring roadside attention. The exclusive focus of this study
133 was crashes leading to cyclist casualties.

134 As shown in Figure 1, this study analysed 1,366,196 crashes involving bicycles and other
135 vehicles. Initially, 1,235,032 junction cases were excluded. From the remaining 131,164 bicycle
136 segment crashes, 3,527 were further excluded because of incomplete demographic data for the
137 cyclist and missing speed limit information, leaving a valid cohort of 127,637 bicycle segment
138 crashes for analysis. Within this cohort, this study identified 18,350 overtaking crashes, 44,962
139 rear-end crashes, 6,363 door crashes, and 57,962 other types of crashes.



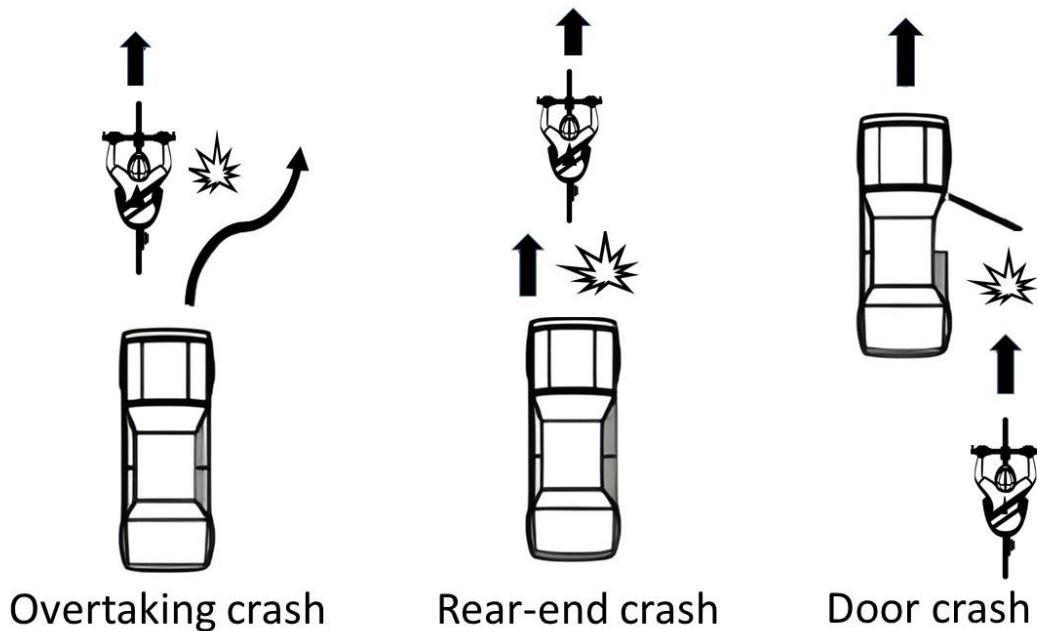
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141 **Figure. 1.** Flowchart of the study sample selection process. ^aListed excluded criteria are nonexclusive; thus, the
142 sum of the total may exceed 3,527. ^bOther crashes include reversing crashes and head-on crashes.

143

144 **Classification of crash types**

145 As shown in Figure 2, an overtaking crash is defined as a crash where a motorised vehicle
146 overtakes and impacts with a bicycle, which may be travelling straight, overtaking another vehicle,
147 changing lanes, or turning. A rear-end crash occurs when a following vehicle impacts with the
148 rear of a bicycle. A door crash involves a bicycle either being struck by or striking the opening
149 door of an automobile. These three crash types were described using schematics in our previous
150 study [18].



154 **Figure 2.** Illustrative diagram of the three crash types

155 **Data collection**

156 For the present study, the three crash types of focus (overtaking, rear-end, and door crashes)
were the binary-dependent variables. The collected data encompassed the following factors:
lighting conditions on the roadway at the time of the crash (daylight, darkness-lit, darkness-unlit),

157 the speed limit at the crash scene (rural: ≥ 40 miles per hour [mph]; urban: 20–30 mph), the time
158 of day categorised into four periods according to traffic volume (midnight: 00:00–06:00; rush
159 hours: 07:00–08:00 and 17:00–18:00; nonrush hours: 09:00–16:00; and evening: 19:00–23:00),
160 and the day of the week (weekday or weekend day). The demographic details of cyclist casualties
161 encompassed age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex (male or female). Finally, the
162 demographic details of the crash partner included the type of vehicle (identified as a taxi, private
163 hire car, car, bus, or heavy goods vehicle [HGV]), age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex
164 (male or female). On a cautionary note, we removed junction cases to avoid the variability
165 introduced when exogenous factors, such as junction geometry and control measures, are
166 present at junctions. Furthermore, the cases involving other cyclists and motorcyclists were
167 removed as we focused on vehicle-cycle crashes only. Missing data on sex, age, or speed limits
168 were also excluded in the analysis. Excluding these data may impact our results in a marginal
169 scale, as these data are likely to be single-bicycle crashes that in nature be underreported in
170 police crash dataset [21].

171

172 **Statistical analysis**

173 This study employed the chi-squared test to examine the associations between crash type and
174 other factors, including cyclist or motorist characteristics, vehicle features, roadway conditions,
175 and temporal variables. Initially, we examined the distribution of three crash types across various
176 variables to explore their relationships with a binary outcome. These variables included lighting
177 conditions, speed limit, time of day, and day of the week. Demographic details concerning cyclist
178 casualties encompassed age and sex, while information about the crash partner included vehicle

179 type, age, and sex. We set a significance level of $p < 0.2$ to include risk factors in our multivariate
180 analysis [23]. Adjusted odds ratios (AORs) were computed using multivariate logistic regression
181 with backward selection.[22, 23]

182 The multivariate logistic regression model equation was specified as:

$$183 \quad \log \left(\frac{P(Y = 1)}{1 - P(Y = 1)} \right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

184 where $P(Y = 1)$ denotes the probability of the outcome, $\beta_0, \beta_1, \beta_2, \dots, \beta_p$ are the coefficients to be
185 estimated, and X_1, X_2, \dots, X_p represent the predictor variables.

186 Before estimating the model, assumptions of logistic regression, such as linearity of the logit,
187 absence of multicollinearity, and independence of observations, were evaluated. An odds ratio
188 (OR) greater than 1 indicated a positive association between the independent variable and the
189 occurrence rate, while an OR less than 1 indicated a negative association. An OR of 1 suggested
190 no association between the variables of interest and the outcomes. All statistical analyses were
191 conducted using SPSS Statistics version 25 for Windows (IBM Corp., Armonk, New York, USA). A
192 p value lower than 0.05 in two-tailed tests was considered statistically significant.

193

194 **Results**

195 **Population characteristics**

196 Tables 1, 2, and 3 present the distributions of overtaking, rear-end, and door crashes, respectively,
197 in relation to multiple independent variables. These data revealed that a significant proportion

198 of bicycle crashes occurred in daylight (82.3%), occurred in urban settings (78.5%), occurred
 199 during nonrush hours (48.3%), occurred on weekdays (77.5%), involved cyclists aged under 18
 200 years (40.1%), and involved male cyclists (81.3%). Additionally, most crashes involved cars as
 201 crash partners (83.6%), and crash partners were predominately aged 19–40 years (38.5%) and
 202 were male (76.4%). Table 1 highlights an overrepresentation in bicycle overtaking crashes for
 203 certain variables, namely unlit darkness (19.5%), rural areas (24.8%), midnight hours (17.7%),
 204 buses or HGVs as crash partners (24.7%), and elderly crash partners (21.5%) and male crash
 205 partners (16.0%). These results were revealed to be statistically significant by the chi-squared
 206 test ($p < 0.01$).

207

208 **Table 1.** Distribution of overtaking crashes according to a set of independent variables

Variable	Total (n=127,637)	Overtaking crashes (n=18,350)	Non-overtaking crashes (n=109,287)	χ^2 test <i>p</i> value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	15,283 (14.55%)	89,770 (85.5%)	
Darkness-lit	16,543 (13.0%)	1,889 (11.42%)	14,654 (88.6%)	
Darkness-unlit	6,041 (4.7%)	1,178 (19.50%)	4,863 (80.5%)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5%)	6,805 (24.8%)	20,590 (75.6%)	
Urban (20–30 mph)	100,242 (78.5%)	11,545 (11.5%)	88,697 (88.5%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	852 (17.7%)	3,958 (82.3%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	5,685 (13.7%)	35,934 (86.3%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	9,386 (15.2%)	52,310 (84.8%)	
Evening (19:00–23:00)	19,512 (15.3%)	2,427 (12.4%)	17,085 (87.6%)	
Crash day, n (%)				0.094
Weekend	28,730 (22.5%)	4,218 (14.7%)	24,512 (85.2%)	
Weekday	98,907 (77.5%)	14,132 (14.3%)	84,775 (85.7%)	
Cyclist's age (years), n (%)				<0.001
≤ 18	51,193 (40.1%)	5,220 (10.2%)	45,973 (89.8%)	
19–40	45,760 (35.9%)	7,108 (15.5%)	38,652 (84.5%)	
41–64	26,052 (20.4%)	5,012 (19.2%)	21,040 (80.8%)	
≥ 65	4,632 (3.6%)	1,010 (21.8%)	3,622 (78.2%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	14,746 (14.2%)	89,020 (85.8%)	
Female	23,871 (18.7%)	3,604 (15.1%)	20,267 (84.9%)	
Crash partner, n (%)				<0.001

Taxi/Private hire car	2,588 (2.0%)	208 (8.0%)	2,380 (92.0%)	
Car	106,668 (83.6%)	13,599 (12.8%)	93,069 (87.3%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	4,543 (24.7%)	13,838 (75.3%)	
Crash partner's age (years), n (%)				<0.001
≤18	2,415 (1.9%)	281 (11.6%)	2,134 (88.4%)	
19–40	49,103 (38.5%)	5,398 (11.0%)	43,705 (89.0%)	
41–64	35,598 (27.9%)	3,973 (11.2%)	31,625 (88.8%)	
≥65	40,521 (31.8%)	8,698 (21.5%)	31,823 (78.5%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.4%)	15,584 (16.0%)	81,863 (84.0%)	
Female	30,190 (23.8%)	2,766 (9.2%)	27,424 (90.8%)	

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210 Several variables in Table 2 reveal significant differences between rear-end crashes and non-
 211 rear-end crashes. Specifically, a higher proportion of rear-end crashes occurred under darkness-
 212 unlit conditions (50.2%) compared to darkness-lit conditions (37.5%). Additionally, rear-end
 213 crashes were more prevalent in rural areas with speed limits of ≥ 40 mph (43.0%) compared to
 214 urban areas with speed limits of 20–30 mph (33.1%). Crashes involving crash partners aged ≥ 65
 215 accounted for 39.7% of rear-end crashes, which was higher compared to other age groups (age
 216 41–64: 33.0% and ≤18: 36.0%). Furthermore, rear-end crashes were more likely to occur during
 217 midnight (47.6%) compared to rush hours (36.3%). Taxis were frequently involved in rear-end
 218 crashes (42.4%), as were male crash partners (36.8%). These findings highlight the significant
 219 influence of various factors on the likelihood of rear-end crashes. Variables such as darkness-unlit
 220 conditions, higher speed limits in rural areas, crash time, and characteristics of the crash partner
 221 all emerged as significant determinants. Specifically, rear-end crashes were notably more
 222 prevalent under darkness-unlit conditions, in rural areas with higher speed limits, during
 223 midnight hours, and involving certain characteristics of crash partners. Importantly, these
 224 associations were statistically significant, as indicated by the Chi-squared test ($p < 0.001$).

225

226 **Table 2.** Distribution of rear-end crashes according to a set of independent variables

Variable	Total (n=127,637)	Rear-end crashes (n=44,962)	Non-rear-end crashes (n=82,675)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	35,726 (34.1%)	69,333 (66.0%)	
Darkness-lit	16,543 (13.0%)	6,204 (37.5%)	10,339 (63.5%)	
Darkness-unlit	6,041 (4.73%)	3,032 (50.19%)	3,003 (49.71%)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5%)	11,788 (43.0%)	15,607 (57.0%)	
Urban (20–30 mph)	100,242 (78.5%)	33,174 (33.1%)	67,068 (66.9%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	2,289 (47.6%)	2,521 (52.4%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	15,089 (36.3%)	26,530 (63.7%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	20,723 (33.6%)	40,973 (66.4%)	
Evening (19:00–23:00)	19,512 (15.3%)	6,861 (36.2%)	12,651 (64.9%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5%)	9,485 (33.0%)	19,245 (67.0%)	

Weekday	98,907 (77.5%)	35,477 (35.9%)	63,430 (64.1%)	
Cyclist's age (years), n (%)				<0.001
≤18	51,193 (40.1%)	13,446 (26.3%)	37,747 (73.7%)	
19–40	45,760 (35.9%)	19,102 (41.7%)	26,658 (58.3%)	
41–64	26,052 (20.4%)	10,619 (40.8%)	15,433 (59.2%)	
≥65	4,632 (3.6%)	1,795 (38.8%)	2,837 (61.3%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	37,175 (35.8%)	66,591 (64.2%)	
Female	23,871 (18.7%)	7,787 (32.6%)	16,084 (67.4%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	1,096 (42.4%)	1,492 (57.7%)	
Car	106,668 (83.6%)	37,202 (34.9%)	71,342 (66.9%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	6,664 (36.3%)	9,841 (53.5%)	
Crash partner's age (years), n (%)				<0.001
≤18	2,415 (1.9%)	870 (36.0%)	1,545 (64.0%)	
19–40	49,103 (38.5%)	16,282 (33.2%)	32,821 (66.8%)	
41–64	35,598 (27.9%)	11,736 (33.0%)	23,862 (67.0%)	
≥65	40,521 (31.8%)	16,074 (40.0%)	24,447 (60.3%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.6%)	35,828 (36.8%)	61,619 (63.2%)	
Female	30,190 (23.7%)	9,134 (30.3%)	21,056 (69.7%)	

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228 As shown in Table 3, several variables can contribute to door crashes involving bicycles. Door
229 crashes predominantly occurred in urban areas with speed limits of 20-30 mph (6.2%), while a
230 significantly lower proportion occurred in rural areas with speed limits ≥ 40 mph (0.5%). These
231 crashes were overrepresented during non-rush hours (5.5%) and rush hours (4.9%) compared to
232 evening (4.3%) and midnight (2.4%). Cyclists were more frequently involved in door crashes on
233 weekdays (5.4%) than weekends (3.7%). As many as 8.2% of all female cyclists were involved in
234 door crashes, which is higher than the involvement rate among males (4.2%). Taxi and private
235 hire cars were overinvolved in door crashes (10.6%) compared to cars (5.2%) and buses/heavy
236 goods vehicles (3.1%). Crash partners aged ≤18 years (5.2%) and 19-40 years (5.3%) were
237 disproportionately involved in door crashes compared to older age groups, and female crash
238 partners were overrepresented in door crashes (7.4%) compared to males (4.2%). These results
239 were statistically significant, as indicated by the Chi-squared test ($p < 0.001$). They suggest that
240 various factors—including traffic conditions (rural areas, crash time), cyclist demographics

241 (younger age, gender), and characteristics of the crash partner (taxi/private hire cars)—
 242 significantly contribute to the likelihood of door crashes involving cyclists.

243 **Table 3.** Distribution of door crashes according to a set of independent variables

Variable	Total (n=127,637)	Door crashes (n=6,363)	Non-door crashes (n=121,274)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	5,192 (4.9%)	99,861 (95.1%)	
Darkness-lit	16,543 (13.0%)	1,031 (6.2%)	15,512 (93.8%)	
Darkness-unlit	6,041 (4.7%)	140 (2.3%)	5,901 (97.7%)	
Speed limit, n (%)				<0.001
Rural (\geq 40 mph)	27,395 (21.5%)	123 (0.5%)	27,272 (99.6%)	
Urban (20–30 mph)	100,242 (78.5%)	6,240 (6.2%)	94,002 (93.8%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	113 (2.4%)	4,697 (97.7%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	2,056 (4.9%)	39,563 (95.1%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	3,363 (5.5%)	58,333 (94.6%)	
Evening (19:00–23:00)	19,512 (15.3%)	831 (4.3%)	18,681 (95.7%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5%)	1,072 (3.7%)	27,658 (96.3%)	
Weekday	98,907 (77.5%)	5,291 (5.4%)	93,616 (94.7%)	
Cyclist's age (years), n (%)				<0.001
\leq 18	51,193 (40.1%)	802 (1.6%)	50,391 (98.4%)	
19–40	45,760 (35.9%)	3,474 (7.6%)	42,286 (93.4%)	
41–64	26,052 (20.4%)	1,773 (6.8%)	24,279 (93.2%)	
\geq 65	4,632 (3.6%)	314 (6.8%)	4,318 (93.2%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	4,404 (4.2%)	99,362 (95.8%)	
Female	23,871 (18.7%)	1,959 (8.2%)	21,912 (91.8%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	273 (10.6%)	2,315 (89.5%)	
Car	106,668 (83.6%)	5,514 (5.2%)	101,154 (94.8%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	576 (3.1%)	17,805 (96.9%)	
Crash partner's age (years), n (%)				<0.001
\leq 18	2,415 (1.9%)	1,62 (5.2%)	2,253 (93.3%)	
19–40	49,103 (38.5%)	2,585 (5.3%)	46,518 (94.7%)	
41–64	35,598 (27.9%)	1,887 (5.3%)	33,711 (94.7%)	
\geq 65	40,521 (31.8%)	1,729 (4.3%)	38,792 (95.7%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.6%)	4,123 (4.2%)	93,324 (95.8%)	
Female	30,190 (23.7%)	2,240 (7.4%)	27,950 (92.6%)	

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246 **Risk factors for the three crash types**

247 Table 4 presents the logistic regression model results. Regarding overtaking crashes, the

248 identified risk factors included daylight conditions (adjusted odds ratio [AOR] = 1.233, 95%

249 confidence interval [CI] = 1.162–1.309; $p < 0.001$), speed limits of ≥ 40 mph (AOR = 2.238, 95% CI =
250 2.159–2.320; $p < 0.001$), nonrush hours (AOR = 1.091, 95% CI 1.031–1.154; $p = 0.003$), cyclists aged
251 ≥ 65 years (AOR = 1.785, 95% CI = 1.649–1.931; $p < 0.001$), female cyclists (AOR = 1.106, 95% CI =
252 1.062–1.153), HGVs as crash partners (AOR = 2.867, 95% CI = 2.473–3.323; $p < 0.001$), elderly crash
253 partners (AOR = 2.013, 95% CI = 1.937–2.092; $p < 0.001$), and male crash partners (AOR = 1.353,
254 95% CI = 1.292–1.416; $p < 0.001$).

255 For rear-end crashes, noteworthy risk factors included unlit darkness (AOR = 1.486, 95% CI
256 = 1.404–1.573; $p < 0.001$), speed limits of ≥ 40 mph (AOR = 1.315, 95% CI = 1.277–1.354; $p < 0.001$),
257 weekdays (AOR = 1.090, 95% CI = 1.059–1.122; $p < 0.001$), midnight hours (AOR = 1.269, 95% CI =
258 1.190–1.354; $p < 0.001$), and taxis as crash partners (AOR = 1.286, 95% CI = 1.186–1.394; $p < 0.001$).

259 Regarding door crashes, significant risk factors included lit darkness (AOR = 1.373, 95% CI =
260 1.141–1.651; $p < 0.001$), speed limits of 20–30 mph (AOR = 16.185, 95% CI = 13.514–19.382;
261 $p < 0.001$), weekdays (AOR = 1.246, 95% CI = 1.162–1.336; $p < 0.001$), and nonrush hours (AOR =
262 2.912, 95% CI = 2.384–3.556; $p < 0.001$). Additionally, female cyclists (AOR = 1.675, 95% CI = 1.582–
263 1.774; $p < 0.001$), taxis or private hire cars as crash partners (AOR = 2.695, 95% CI = 2.310–3.145;
264 $p < 0.001$), male crash partners (AOR = 1.373, 95% CI = 1.296–1.455; $p < 0.001$), and crash partners
265 aged 41–64 years (AOR = 1.855, 95% CI = 1.625–2.117; $p < 0.001$) were associated with door
266 crashes.

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274 **Table 4.** Multivariate logistic regression results

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Light condition						
Daylight	1.233 (1.162, 1.309)	<0.001	Ref		1.146 (0.958, 1.370)	0.137
Darkness-lit	Ref		1.042 (1.002, 1.085)	0.041	1.373 (1.141, 1.651)	0.001
Darkness-unlit	1.152 (1.059, 1.253)	0.001	1.486 (1.404, 1.573)	<0.001	Ref	
Speed limit						
Rural (≥40 mph)	2.238 (2.159, 2.320)	<0.001	1.315 (1.277, 1.354)	<0.001	Ref	
Urban (20–30 mph)	Ref		Ref		16.185 (13.514, 19.382)	<0.001
Crash time						
Midnight	1.073 (0.982, 1.173)	0.119	1.269 (1.190, 1.354)	<0.001	Ref	
Rush hours	1.059 (1.002, 1.120)	0.043	1.108 (1.078, 1.139)	<0.001	2.502 (2.051, 3.052)	<0.001
Nonrush hours	1.091 (1.031, 1.154)	0.003	Ref		2.912 (2.384, 3.556)	<0.001
Evening	Ref		0.992 (0.953, 1.032)	0.686	2.014 (1.646, 2.465)	<0.001

Table 4. Multivariate logistic regression results (*continued*)

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Crash day						
Weekend	1.031 (0.991, 1.072)	0.132	Ref		Ref	
Weekday	Ref		1.090 (1.059, 1.122)	<0.001	1.246 (1.162, 1.336)	<0.001
Cyclist's age (years)						
≤18	Ref		Ref		Ref	
19–40	1.292 (1.242, 1.345)	<0.001	1.839 (1.788, 1.891)	<0.001	5.943 (5.489, 6.435)	<0.001
41–64	1.509 (1.444, 1.578)	<0.001	1.731 (1.676, 1.789)	<0.001	6.129 (5.621, 6.684)	<0.001
≥65	1.785 (1.649, 1.931)	<0.001	1.671 (1.568, 1.780)	<0.001	5.988 (5.217, 6.874)	<0.001
Cyclist's sex						
Male	Ref		1.172 (1.137, 1.208)	<0.001	Ref	
Female	1.106 (1.062, 1.153)	<0.001	Ref		1.675 (1.582, 1.774)	<0.001
Crash partner						
Taxi/Private hire car	Ref		1.286 (1.186, 1.394)	<0.001	2.695 (2.310, 3.145)	<0.001
Car	1.571 (1.359, 1.816)	<0.001	Ref		2.089 (1.908, 2.286)	<0.001
Bus/Heavy goods vehicle	2.867 (2.473, 3.323)	<0.001	1.099 (1.061, 1.139)	<0.001	Ref	
Crash partner's age (years)						
≤18	1.097 (0.963, 1.249)	0.162	1.225 (1.188, 1.263)	<0.001	1.507 (1.313, 1.731)	<0.001
19–40	Ref		1.038 (1.008, 1.069)	0.013	1.855 (1.625, 2.117)	<0.001
41–64	0.950 (0.909, 0.994)	0.025	Ref		1.801 (1.574, 2.060)	<0.001
≥65	2.013 (1.937, 2.092)	<0.001	1.241 (1.137, 1.355)	<0.001	Ref	
Crash partner's sex						
Male	1.353 (1.292, 1.416)	<0.001	1.150 (1.117, 1.185)	<0.001	1.373 (1.296, 1.455)	<0.001
Female	Ref		Ref		Ref	

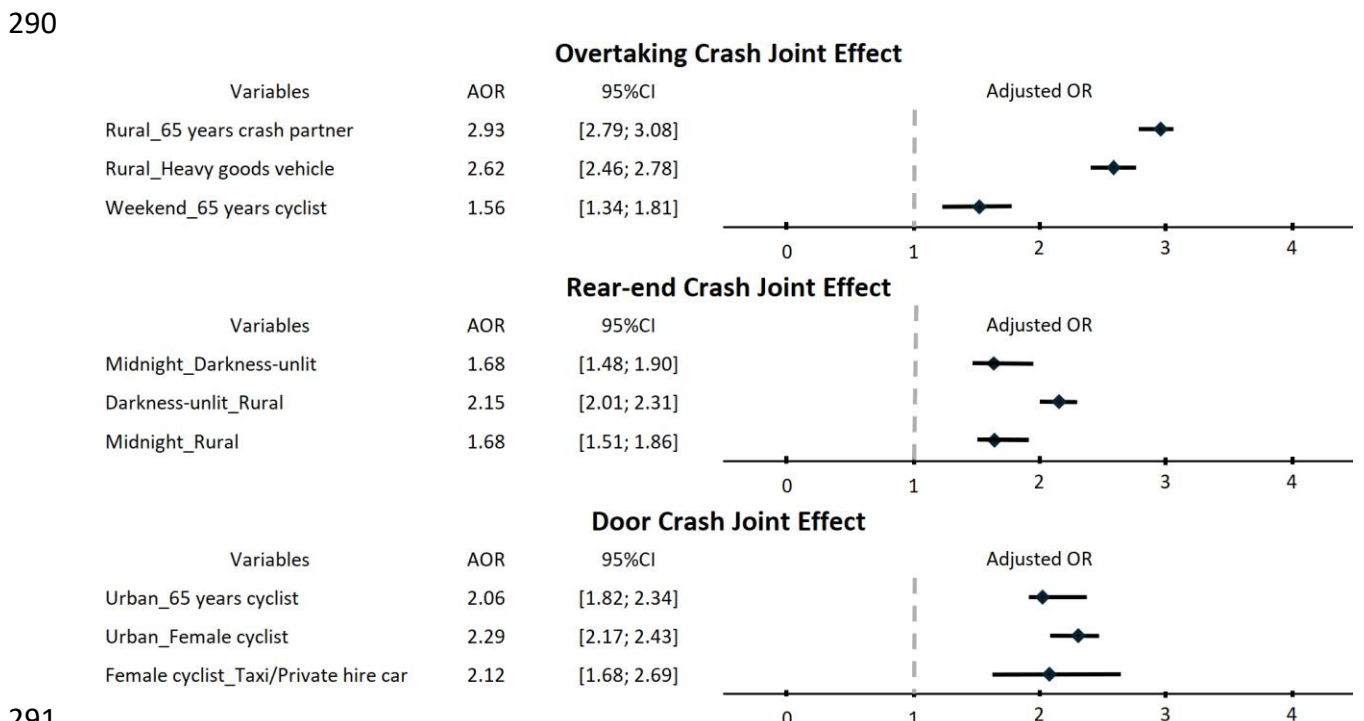
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276 Figure 2 presents a forest plot demonstrating the joint effects of several variables on the

277 three crash types when other variables were controlled for. The results identified several key risk

278 factors for both overtaking and rear-end crashes. The risk of overtaking crashes showed a
 279 significant increase of 193% in rural areas when elderly drivers were involved (AOR = 2.93, 95%
 280 CI = 2.79–3.08), and similarly when heavy goods vehicles (HGVs) were the crash partner (AOR =
 281 2.62, 95% CI = 2.46–2.78). Elderly cyclists also faced a higher risk of overtaking crashes on
 282 weekends (AOR = 1.56, 95% CI = 1.34–1.81).

283 Regarding rear-end crashes, the risk increased notably with unlit darkness during
 284 midnight (AOR = 1.68, 95% CI = 1.48–1.90) and was significantly higher in rural areas (AOR = 2.15,
 285 95% CI = 2.01–2.31). Furthermore, bicycling at midnight in rural areas was associated with an
 286 increased risk of rear-end crashes (AOR = 1.68; 95% CI = 1.51–1.86). In urban settings, the risk of
 287 door crashes was higher for female cyclists (AOR = 2.29; 95% CI = 2.17–2.43) and for elderly
 288 cyclists (AOR = 2.06; 95% CI = 1.82–2.34). Finally, female cyclists exhibited a 112% higher
 289 likelihood of door crashes when the crash partner was a taxi (AOR = 2.12; 95% CI = 1.68–2.69).



291 **Figure. 3.** Joint effects of several variables on the three crash types.
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Discussion

298 This study explored the relationships among individual and environmental factors in relation to
299 three common bicycle crash types (overtaking, rear-end, and door crashes) on roads in the United
300 Kingdom from 1991 to 2020. The findings revealed several significant factors. First, for overtaking
301 crashes, HGVs as crash partners, rural areas, and the involvement of elderly crash partners
302 emerged as key contributing factors. Second, unlit darkness, midnight hours, and rural areas
303 were the factors most closely associated with rear-end crashes. Third, urban areas and taxis as
304 crash partners significantly increased the likelihood of door crashes. Moreover, male crash
305 partners were found to be a consistent risk factor across all three crash types.

306 Our research findings identified specific risk factors for overtaking crashes, namely rural
307 areas, HGVs as crash partners, and elderly crash partners. These findings align with previous
308 research that identified elderly drivers [24], speeds exceeding 10 mph, and the presence of pick-
309 up trucks as factors contributing to increased risk for overtaking crash. Specifically, HGVs possess
310 several characteristics that amplify this danger. Their large blind spots make it difficult for drivers
311 to see cyclists, increasing the likelihood of crashes during overtaking. Additionally, HGVs are less
312 manoeuvrable compared to passenger cars, which reduces their ability to avoid crashes if cyclists
313 suddenly enter their path. The speed and distance perception issues between HGVs and cyclists
314 further complicate the judgment of safe overtaking gaps. Furthermore, HGVs require longer
315 stopping distances due to their size and weight, which can lead to severe consequences if a
316 sudden need to brake arises. A behavioural study suggested that compared with cars, HGVs

317 tended to maintain a narrower clearance zone when overtaking bicycles [25]. Regarding the
318 association with buses or HGVs, Pai et al. [18] suggested that time pressures on HGV drivers for
319 timely loading and unloading might lead to more reckless driving. Specifically, our results align
320 with the observations made by Pai et al., who also mentioned higher crash rates involving buses
321 or HGVs, supporting the idea that these time pressures contribute to increased crash risks. Our
322 findings underscore the necessity of implementing measures such as ‘Share the Road’ warning
323 signs [26], particularly in rural settings, where HGVs are likely to execute overtaking manoeuvres
324 at high speed. Such measures could prompt motor vehicles to maintain safer distances from the
325 edges of travel lanes, especially in areas with a notable presence of both HGVs and bicycles.

326 We also identified elderly drivers as a factor contributing to overtaking crashes—a finding
327 consistent with relevant research [24]. We found that as individuals age, their risk of being
328 involved in road accidents increases, primarily due to declines in cognitive capabilities. Our study
329 corroborates these findings by showing that older cyclists are more susceptible to accidents
330 during overtaking manoeuvres, which can be attributed to diminished reaction times and
331 impaired decision-making abilities [27], their health [28], and their driving performance [29].
332 Notably, crashes involving elderly individuals often occur in scenarios with challenging conditions,
333 including at intersections without traffic control measures, on high-speed roads, during adverse
334 weather conditions, in poorly lit areas, and in head-on accidents [30-32]. The heightened level of
335 risk under such conditions may be attributed to cognitive and perceptual decline in older drivers,
336 which could affect their capacity to execute actions such as overtaking manoeuvres safely.
337 Accordingly, developing specialised cognitive training programmes as interventions to enhance
338 road safety for elderly drivers is evidently necessary [33]. Based on our study's findings, we

339 recommend the development of specialised interventions to improve road safety for elderly
340 cyclists. Our analysis reveals that older cyclists are at a higher risk of being involved in overtaking
341 crashes, with this increased risk being strongly linked to declines in cognitive capabilities
342 associated with aging. To address this issue, we advocate for the implementation of targeted
343 cognitive training programs specifically designed for elderly cyclists. These programs should focus
344 on enhancing critical skills such as reaction time, situational awareness, and decision-making
345 abilities, which are crucial for reducing crash risk and improving overall road safety.

346 In the present study, several factors were found to increase the risk of rear-end crashes on
347 road segments, including darkness with unlit surroundings, midnight hours, and rural settings
348 (speed limit > 40 mph). Although few studies have specifically addressed rear-end crashes
349 involving bicycles on road segments, available data suggest that the low conspicuity of bicycles,
350 especially at night, is a recurrent factor in rear-end crashes [18, 34]. Moreover, a lack of adequate
351 street lighting, which is common in rural settings, predisposes cyclists to rear-end crashes [18].
352 Our joint-effects analysis further indicated that the detrimental effect of unlit darkness is more
353 pronounced in rural areas and during midnight hours. Potential intervention strategies to
354 mitigate rear-end crashes include enhancing illumination and executing speed control
355 management on rural road segments with heavy bicycle traffic.

356 Next, our analysis successfully identified associations of urban areas and taxis and private
357 hire cars as crash partners with door crashes on road segments. Although research specifically
358 focusing on door crashes on road segments is limited, similar findings were documented by Pai,
359 indicating that urban roadways and taxis contributed to door crashes [18]. However, determining
360 the factors influencing this trend poses a challenge. One possible explanation could be the

361 increased presence of taxis or private hire cars in such areas, where passengers often disembark.
362 Additionally, our analysis further revealed an elevated risk of door crashes involving crashes with
363 taxis in urban areas. To reduce door crashes on road segments, educating taxi drivers, as well as
364 passengers, about the importance of vigilance when opening doors near traffic is essential [18].
365 In addition, cyclists should be advised to maintain at least a door's width distance from all parked
366 cars to improve the sight triangles of drivers and increase the visibility of cyclists [35].
367 Implementing a two-stage door opening mechanism for vehicles, which would enable drivers to
368 verify the presence of bicycles to the rear, could also be beneficial [36].

369 The strengths of this study include the use of STATS19 datasets spanning from 1991 to 2020,
370 which provides a robust statistical foundation and a broad perspective on trends in bicycle
371 crashes. By focusing specifically on three crash types on road segments—overtaking, rear-end,
372 and door crashes—the study provides a comprehensive and focused analysis, which can yield
373 more actionable insights and more effective recommendations. The UK-based dataset ensures
374 that the findings are particularly relevant for local policy and safety interventions. Additionally,
375 the application of statistical techniques and the consideration of various factors, such as crash
376 partner and time of day, enhance the validity and depth of the analysis.

377 This study had several limitations that warrant acknowledgement. First, the substantial
378 underreporting of nonfatal casualties to the police, particularly casualties involving cyclists not
379 obligated to report accidents, is a critical factor to consider. Such underreporting, as highlighted
380 by the U.K. Government's Department for Transport [11], likely results in the incomplete
381 representation of nonfatal and 'slight' casualties in road casualty data. Second, the STATS19 data
382 utilised in this study lack critical variables, including precrash speeds, specific geometric

383 characteristics of roadways, data regarding alcohol and illicit substance use, and cyclist speed at
384 the time of an accident. Moreover, critical exposure data—such as those related to traffic flow,
385 rider or driver experience, and other elements of risk exposure—are absent, and the absence of
386 such details limits our ability to fully account for potential variations resulting from unobserved
387 factors in the analyses. Finally, this study did not explore annual trends in each type of bicycle
388 crash over the 30-year study period; investigating such trends could provide insights regarding
389 changing behaviours among cyclists and motor vehicle drivers as well as the effects of legislative
390 changes for road speed limits.

391 One inherent problem with police-reported crash data is the variables not readily available,
392 hereby causing unobserved heterogeneity across the observations. To overcome such a
393 limitation, we estimated separate regression models, as suggested by Kim et al.[37], for the three
394 crash types; such an approach provides greater explanatory power compared to single overall
395 models. Further, we conducted joint-effect analyses of several variables of interest that capture
396 heterogeneity. In our previous studies, we adopted the above-mentioned approaches to
397 overcome the inherent problem with a success [38, 39].

398 Future research directions could involve integrating GPS (Global Positioning System) data
399 and weather conditions to analyse both injury frequency and fatalities of bicycle crashes on road
400 segments. Additionally, exploring the potential of autonomous vehicles for detecting
401 approaching bicycles for door-crashes and implementing AI-controlled lighting systems in rural
402 areas for cyclist detection could be promising areas for further study.

403

404 **Recommendations**

405 For overtaking crashes, we recommend implementing 'Share the Road' warning signs,
406 especially in rural areas, and developing specialized cognitive training programs for elderly
407 drivers. Regarding rear-end crashes, our suggestions include improving illumination during night
408 time and implementing speed control measures on rural road segments. For door crashes
409 involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility.
410 Moreover, implementing a two-stage door opening mechanism and an automatic detection
411 device in vehicles to alert drivers of bicycles approaching from behind could potentially be
412 beneficial.

413

414 **Conclusions**

415 This study identified several significant risk factors for the three predominate types of crashes
416 involving cyclists on road segments: HGVs as crash partners, elderly crash partners, and rural
417 areas for overtaking crashes; unlit darkness, midnight hours, and rural areas for rear-end crashes;
418 and urban areas and taxis as crash partners for door crashes. These risk factors remained
419 unchanged since our previous study conducted in 2011 [15]. The present research enhances the
420 field of bicycle safety research by concluding that the detrimental effects of certain variables
421 become more pronounced under certain conditions. For example, first, cyclists in rural settings
422 exhibited an elevated risk of overtaking crashes involving HGVs. Second, the rear-end crash risk
423 increases in the combined presence of unlit darkness, midnight hours, and rural areas. Finally, in
424 urban settings, the likelihood of door crashes increases when a taxi is the crash partner.

425

426 **Abbreviations**

427 WHO: World Health Organization; HGVs: heavy goods vehicles; AOR: adjusted odds ratio; CI:
428 confidence interval.

429

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432

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448 interpretation of data, or preparation of the manuscript.

449

450 **Availability of data and materials**

451 This study utilised the British STATS19 database, which contains data on all road traffic accidents
452 in the United Kingdom. The data that support the findings of this study are openly available at
453 <https://figshare.com/ndownloader/files/48173452>.

454

455 **Declarations**

456 **Ethical approval and consent to participate**

457 This study was conducted in accordance with the Declaration of Helsinki and approved by the
458 Joint Institutional Review Board of Taipei Medical University (N202011030).

459

460 **Consent for publication**

461 This study was approved by the Joint Institutional Review Board of Taipei Medical
462 University (N202011030). The Joint Institutional Review Board of Taipei Medical University has
463 waived the requirement of informed consent. All methods were performed in accordance with
464 the relevant guidelines and regulations of the Declaration of Helsinki.

465

466 **Competing interests**

467 The authors declare that they have no competing interests in relation to this work.

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573 opportunistic, and law-obeying behaviours. *Accident Analysis & Prevention*. 2014;62:191-8.
574

1 **Risk Factors for Overtaking, Rear-End, and Door Crashes Involving Bicycles in the United**
2 **Kingdom: Revisited and Reanalysed**
3

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22 **Abstract**

23 **Background and Objective:** Relevant research has provided valuable insights into risk factors for
24 bicycle crashes at intersections. However, few studies have focused explicitly on three common
25 types of bicycle crashes on road segments: overtaking, rear-end, and door crashes. This study
26 aims to identify risk factors for overtaking, rear-end, and door crashes that occur on road
27 segments.

28 **Material and methods**

29 We analysed British STATS19 accident records from 1991 to 2020. Using multivariate logistic
30 regression models, we estimated adjusted odds ratios (AORs) with 95% confidence intervals (CIs)
31 for multiple risk factors. The analysis included 127,637 bicycle crashes, categorised into 18,350
32 overtaking, 44,962 rear-end, 6,363 door, and 57,962 other crashes.

33 **Results**

34 Significant risk factors for overtaking crashes included heavy goods vehicles (HGVs) as crash
35 partners (AOR = 1.30, 95% CI 1.27–1.33), and elderly crash partners (AOR = 2.01, 95% CI = 1.94-
36 2.09), and decreased risk in rural area with speed limits of 20-30 miles per hour (AOR = 0.45 ,
37 95% CI =0.43-0.47). For rear-end crashes, noteworthy risk factors included unlit darkness (AOR =
38 1.49, 95% CI = 1.40–1.57) and midnight hours (AOR = 1.28, 95% CI = 1.21–1.40). Factors
39 associated with door crashes included urban areas (AOR = 16.2, 95% CI = 13.5–19.4) and taxi or
40 private hire cars (AOR = 1.61, 95% CI =1.57–1.69). Our joint-effect analysis revealed additional
41 interesting results; for example, there were elevated risks for overtaking crashes in rural areas
42 with elderly drivers as crash partners (AOR = 2.93, 95% CI = 2.79–3.08) and with HGVs as crash
43 partners (AOR = 2.62, 95% CI = 2.46–2.78).

44

45 **Conclusions**

46 The aforementioned risk factors remained largely unchanged since 2011, when we conducted
47 our previous study. However, the present study concluded that the detrimental effects of certain
48 variables became more pronounced in certain situations. For example, cyclists in rural settings
49 exhibited an elevated risk of overtaking crashes involving HGVs as crash partners.

50

51 **Keywords:** Bicycle crash; Road segment; Overtaking crash; Rear-end crash; Door crash

52

53

54

55 **Introduction**

56 In recent years, urban bicycling has become increasingly popular in many countries, offering
57 benefits such as reduced traffic congestion, diminished parking pressure, and a reduction in
58 greenhouse gas emissions (1, 2). The World Health Organization has highlighted numerous health
59 advantages of moderate-intensity physical activities such as bicycling, including improvements in
60 life expectancy, quality of life, cognitive function, mental health, sleep quality, muscular and
61 cardiorespiratory fitness, and bone and functional health (1).

62 However, despite such health benefits, the risk of injury remains a considerable safety
63 concern for cyclists, who are regarded as vulnerable road users (1, 3). Traffic crash data indicate
64 that the risk of accidents for cyclists, measured per distance travelled, is approximately 20 times
65 higher than that for vehicle drivers(1). To address this problem, researchers in the United States

66 developed a comprehensive bicycle route safety rating model with a focus on injury severity (4).
67 This model evaluates multiple operational and physical aspects such as traffic volume, population
68 density, highway classification, lane width, and the presence of one-way streets. In addition, it is
69 capable of predicting the severity of injuries due to motor vehicle–related crashes at specific
70 locations (4). Another finding was that a route is considered adequately safe if it includes
71 geometric factors that enhance safety (4). This model can aid urban planners and public officials
72 in creating infrastructure such as bike lanes and implementing strict lane policies to improve
73 cyclist safety (4). Implementing bike lanes has been demonstrated to reduce crash rates by up to
74 40% among adult cyclists (5). One study found that roundabouts with dedicated cycle tracks
75 significantly lower the risk of injury for cyclists compared to those without such bicycle
76 infrastructure. (6). Furthermore, adequate night-time lighting on rural roads has the potential to
77 prevent over half of all cyclist injuries (7). Bicycle crashes can also impose a significant burden on
78 healthcare expenses. Elvik and Sundfør (8) have discussed the economic implications and
79 healthcare expenditures associated with bicycle accidents. For instance, in Belgium, the average
80 cost of bicycle accidents per case is estimated at 841 euros (9). In the Netherlands, the total
81 annual cost has been reported as €410.7 million (10).

82 Although intersectional crashes are generally more frequent than non-intersectional ones, in
83 2020, 64% of fatal crashes involving cyclists occurred on road segments, defined as areas 20
84 meters away from intersections, whereas only 26% of such fatalities occurred at intersections
85 (11). Bil et al. demonstrated that car drivers, when at fault for crashes, often cause more serious
86 consequences for cyclists on straight road sections (12). In crashes occurring on road segments,
87 several factors contribute to high injury severity, including being in a rural region with an elevated

88 speed limit, male gender, and cyclist age of >55 years (13). Another identified risk factor is
89 bicycling on roads against oncoming traffic (14).

90 Although relevant research has shed light on risk factors for bicycle crashes at intersections,
91 few studies have explicitly investigated crashes on road segments. Bicycle crashes on road
92 segments remain a substantial issue for public health concern. This study aims to fill a critical gap
93 by conducting a thorough examination of the risk factors associated with three distinct bicycle
94 crash types: overtaking, rear-end, and door crashes that occur on road segments. Studies that
95 have examined bicycle crashes relatively broadly, without distinguishing crash types, have
96 identified several key factors—including vehicle volume (15), traffic density (16), number of lanes
97 (16), access points along road segments (15), shoulder and median widths (15), parking space
98 availability (15, 16) , length of continuous two-way left-turn lanes (15), and pavement type (17)—
99 all of which contribute to bicycle crashes on road segments. One notable study has examined the
100 risk factors for overtaking, rear-end, and door crashes (18). Specifically, Pai identified buses and
101 coaches as common crash partners in overtaking crashes, poor visibility, traversing manoeuvres,
102 and teenage cyclists as risk factors for rear-end crashes, and built-up areas as a risk factor for
103 door crashes(18) . In addition, another study linked the speed of a passing vehicle to increased
104 severity of cyclist injury in overtaking crashes (19). The high mortality rate from crashes on
105 road segments underscores the significant risks linked to overtaking, rear-end, and door
106 crashes. Overtaking, involving high-speed maneuvers, greatly increases the likelihood of
107 severe accidents. Rear-end crashes, frequently triggered by sudden stops or aggressive
108 tailgating, pose a persistent threat to cyclists. Furthermore, injuries sustained by cyclists
109 striking an opening car door can be devastating due to the impacts from the door, ground, or

110 vehicles behind. These critical issues highlight the urgent need for identifying risk factors for
111 these crashes.

112 The primary objective of the present study, an extension of our previous study, was to analyse
113 police-reported crash data from additional years to determine whether the risk factors for these
114 three crash types remained unchanged. The study addresses a critical gap in current research,
115 focusing on crashes specifically occurring on road segments. Existing literature offers limited
116 insights into these crash types, highlighting a crucial need for targeted investigations. These
117 crashes have the potential for severe impacts, involving complex dynamics that demand a
118 nuanced understanding for effective mitigation strategies. By exploring these factors, our
119 research aims to significantly enhance cyclist safety within this particular context. Furthermore,
120 we aimed to untangle the joint associations of several factors—including light conditions, urban
121 versus rural settings, vehicle types, and rider and driver characteristics—with these three crash
122 types.

123

124 **Material and Methods**

125 **Crash data source**

126 The present investigation utilised data from 01/01/1991 to 31/12/2020, obtained from the
127 United Kingdom’s official road traffic casualty database, STATS19. Police record such data either
128 at crash scenes or within 30 days of each crash. The UK’s Department for Transport compiles the
129 data, which the United Kingdom Data Archive then maintains and distributes. The dataset
130 encompasses a variety of variables, including crash circumstances (e.g., time and date, weather
131 conditions, road and light conditions, posted speed limit, road type), vehicle and driver

132 characteristics, demographic details of the drivers, precrash manoeuvres of the vehicles, and the
133 initial impact point of the vehicle. Additionally, the dataset contains demographic information
134 and details regarding injury severity for each casualty. This study adhered to the STROBE
135 (strengthening the reporting of observational studies in epidemiology) reporting guidelines.(20)
136 The data that support the findings of this study are openly available at
137 <https://figshare.com/ndownloader/files/48173452>.

138 Injury severity in the aforementioned dataset is divided into three categories, namely slight,
139 serious, and fatal. Fatal injuries refer to those leading to death within 30 days of the accident.
140 Serious injuries include conditions such as fractures, internal injuries, severe cuts and lacerations,
141 concussions, and any injury requiring hospitalisation. Slight injuries include sprains, bruises, and
142 minor cuts, as well as mild shock requiring roadside attention. The exclusive focus of this study
143 was crashes leading to cyclist casualties.

144 As shown in Figure 1, this study analysed 1,366,196 crashes involving bicycles and other
145 vehicles. Initially, 1,235,032 junction cases were excluded. From the remaining 131,164 bicycle
146 segment crashes, 3,527 were further excluded because of incomplete demographic data for the
147 cyclist and missing speed limit information, leaving a valid cohort of 127,637 bicycle segment
148 crashes for analysis. Within this cohort, this study identified 18,350 overtaking crashes, 44,962
149 rear-end crashes, 6,363 door crashes, and 57,962 other types of crashes.

150

151

152 **Classification of crash types**

153 As shown in Figure 2, an overtaking crash is defined as a crash where a motorised vehicle
154 overtakes and impacts with a bicycle, which may be travelling straight, overtaking another vehicle,

155 changing lanes, or turning. A rear-end crash occurs when a following vehicle impacts with the
156 rear of a bicycle. A door crash involves a bicycle either being struck by or striking the opening
157 door of an automobile. These three crash types were described using schematics in our previous
158 study(18) .

159

160 **Data analysis**

161 For the present study, the three crash types of focus (overtaking, rear-end, and door crashes)
162 were the binary-dependent variables. The collected data encompassed the following factors:
163 lighting conditions on the roadway at the time of the crash (daylight, darkness-lit, darkness-unlit),
164 the speed limit at the crash scene (rural: ≥ 40 miles per hour [mph]; urban: 20–30 mph), the time
165 of day categorised into four periods according to traffic volume (midnight: 00:00–06:00; rush
166 hours: 07:00–08:00 and 17:00–18:00; nonrush hours: 09:00–16:00; and evening: 19:00–23:00),
167 and the day of the week (weekday or weekend day). The demographic details of cyclist casualties
168 encompassed age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex (male or female). Finally, the
169 demographic details of the crash partner included the type of vehicle (identified as a taxi, private
170 hire car, car, bus, or heavy goods vehicle [HGV]), age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex
171 (male or female). On a cautionary note, we removed junction cases to avoid the variability
172 introduced when exogenous factors, such as junction geometry and control measures, are
173 present at junctions. Furthermore, the cases involving other cyclists and motorcyclists were
174 removed as we focused on vehicle-cycle crashes only. Missing data on sex, age, or speed limits
175 were also excluded in the analysis. Excluding these data may impact our results in a marginal
176 scale, as these data are likely to be single-bicycle crashes that in nature be underreported in

177 police crash dataset (21).

178

179 **Statistical analysis**

180 This study employed the Chi-squared test to examine the associations between crash type and
181 other factors, including cyclist or motorist characteristics, vehicle features, roadway conditions,
182 and temporal variables. We initially utilized descriptive statistics to examine the distribution of
183 crash types across various variables such as lighting conditions, speed limit, time of day, and day
184 of the week. Demographic details concerning cyclist casualties encompassed age and sex, while
185 information about the crash partner included vehicle type, age, and sex. This preliminary analysis
186 provided a general picture of basic characteristics of the data and identification of potential
187 patterns. For inferential analysis, we applied the Chi-squared test to investigate associations
188 between crash type and various factors, including cyclist and motorist characteristics, vehicle
189 features, roadway conditions, and temporal variables. We then estimated crude odds ratios by
190 estimating univariate logistic regression and adjusted odds ratios by multivariate logistic models,
191 respectively. This approach allowed us to identify significant predictors while controlling for
192 potential confounding variables.(22)

193 The multivariate logistic regression model equation was specified as:

$$194 \quad \log \left(\frac{P(Y = 1)}{1 - P(Y = 1)} \right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

195 where $P(Y = 1)$ denotes the probability of the outcome, $\beta_0, \beta_1, \beta_2, \dots, \beta_p$ are the coefficients to be
196 estimated, and X_1, X_2, \dots, X_p represent the predictor variables.

197 Before estimating the model, assumptions of logistic regression, such as linearity of the logit,
198 absence of multicollinearity, and independence of observations, were evaluated. An odds ratio
199 (OR) greater than 1 indicated a positive association between the independent variable and the
200 occurrence rate, while an OR less than 1 indicated a negative association. An OR of 1 suggested
201 no association between the variables of interest and the outcomes. Additionally, joint effect
202 analysis was employed to assess the risk associated with the combination of variables across the
203 three types of crashes. All statistical analyses were conducted using SPSS Statistics version 25 for
204 Windows (IBM Corp., Armonk, New York, USA). A *p* value lower than 0.05 in two-tailed tests was
205 considered statistically significant.

206

207 **Results**

208 **Population characteristics**

209 Tables 1, 2, and 3 present the distributions of overtaking, rear-end, and door crashes,
210 respectively, in relation to multiple independent variables. These data revealed that a significant
211 proportion of bicycle crashes occurred in daylight (82.3%), occurred in urban settings (78.5%),
212 occurred during nonrush hours (48.3%), occurred on weekdays (77.5%), involved cyclists aged
213 under 18 years (40.1%), and involved male cyclists (81.3%). Additionally, most crashes involved
214 cars as crash partners (83.6%), and crash partners were predominately aged 19–40 years (38.5%)
215 and were male (76.4%). Table 1 highlights an overrepresentation in bicycle overtaking crashes
216 for certain variables, namely unlit darkness (19.5%), rural areas (24.8%), midnight hours (17.7%),
217 buses or HGVs as crash partners (24.7%), and elderly crash partners (21.5%) and male crash
218 partners (16.0%). These results were revealed to be statistically significant by the chi-squared

219 test ($p < 0.01$).

220

221 **Table 1.** Distribution of overtaking crashes according to a set of independent variables

Variable	Total (n=127,637)	Overtaking crashes (n=18,350)	Non-overtaking crashes (n=109,287)	χ^2 test <i>p</i> value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3)	15,283 (14.6)	89,770 (85.5)	
Darkness-lit	16,543 (13.0)	1,889 (11.4)	14,654 (88.6)	
Darkness-unlit	6,041 (4.7)	1,178 (19.5)	4,863 (80.5)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5)	6,805 (24.8)	20,590 (75.6)	
Urban (20–30 mph)	100,242 (78.5)	11,545 (11.5)	88,697 (88.5)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8)	852 (17.7)	3,958 (82.3)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6)	5,685 (13.7)	35,934 (86.3)	
Nonrush hours (09:00–16:00)	61,696 (48.3)	9,386 (15.2)	52,310 (84.8)	
Evening (19:00–23:00)	19,512 (15.3)	2,427 (12.4)	17,085 (87.6)	
Crash day, n (%)				0.094
Weekend	28,730 (22.5)	4,218 (14.7)	24,512 (85.2)	
Weekday	98,907 (77.5)	14,132 (14.3)	84,775 (85.7)	
Cyclist's age (years), n (%)				<0.001
≤ 18	51,193 (40.1)	5,220 (10.2)	45,973 (89.8)	
19–40	45,760 (35.9)	7,108 (15.5)	38,652 (84.5)	
41–64	26,052 (20.4)	5,012 (19.2)	21,040 (80.8)	
≥ 65	4,632 (3.6)	1,010 (21.8)	3,622 (78.2)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3)	14,746 (14.2)	89,020 (85.8)	
Female	23,871 (18.7)	3,604 (15.1)	20,267 (84.9)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0)	208 (8.0)	2,380 (92.0)	
Car	106,668 (83.6)	13,599 (12.8)	93,069 (87.3)	
Bus/Heavy goods vehicle	18,381 (14.4)	4,543 (24.7)	13,838 (75.3)	
Crash partner's age (years), n (%)				<0.001
≤ 18	2,415 (1.9)	281 (11.6)	2,134 (88.4)	
19–40	49,103 (38.5)	5,398 (11.0)	43,705 (89.0)	
41–64	35,598 (27.9)	3,973 (11.2)	31,625 (88.8)	
≥ 65	40,521 (31.8)	8,698 (21.5)	31,823 (78.5)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.4)	15,584 (16.0)	81,863 (84.0)	
Female	30,190 (23.8)	2,766 (9.2)	27,424 (90.8)	

222

223 Several variables in Table 2 reveal significant differences between rear-end crashes and non-

224 rear-end crashes. Specifically, a higher proportion of rear-end crashes occurred under darkness-

225 unlit conditions (50.2%) compared to darkness-lit conditions (37.5%). Additionally, rear-end
 226 crashes were more prevalent in rural areas with speed limits of ≥ 40 mph (43.0%) compared to
 227 urban areas with speed limits of 20–30 mph (33.1%). Crashes involving crash partners aged ≥ 65
 228 accounted for 39.7% of rear-end crashes, which was higher compared to other age groups (age
 229 41–64: 33.0% and ≤ 18 : 36.0%). Furthermore, rear-end crashes were more likely to occur during
 230 midnight (47.6%) compared to rush hours (36.3%). Taxis or private hire cars were frequently
 231 involved in rear-end crashes (42.4%), as were male crash partners (36.8%). These findings
 232 highlight the significant influence of various factors on the likelihood of rear-end crashes.
 233 Variables such as darkness-unlit conditions, higher speed limits in rural areas, crash time, and
 234 characteristics of the crash partner all emerged as significant determinants. Importantly, these
 235 associations were statistically significant, as indicated by the Chi-squared test ($p < 0.001$).

236

237 **Table 2.** Distribution of rear-end crashes according to a set of independent variables

Variable	Total (n=127,637)	Rear-end crashes (n=44,962)	Non-rear-end crashes (n=82,675)	χ^2 test <i>p</i> value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3)	35,726 (34.1)	69,333 (66.0)	
Darkness-lit	16,543 (13.0)	6,204 (37.5)	10,339 (63.5)	
Darkness-unlit	6,041 (4.73)	3,032 (50.19)	3,003 (49.71)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5)	11,788 (43.0)	15,607 (57.0)	
Urban (20–30 mph)	100,242 (78.5)	33,174 (33.1)	67,068 (66.9)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8)	2,289 (47.6)	2,521 (52.4)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6)	15,089 (36.3)	26,530 (63.7)	
Nonrush hours (09:00–16:00)	61,696 (48.3)	20,723 (33.6)	40,973 (66.4)	
Evening (19:00–23:00)	19,512 (15.3)	6,861 (36.2)	12,651 (64.9)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5)	9,485 (33.0)	19,245 (67.0)	
Weekday	98,907 (77.5)	35,477 (35.9)	63,430 (64.1)	
Cyclist's age (years), n (%)				<0.001
≤ 18	51,193 (40.1)	13,446 (26.3)	37,747 (73.7)	
19–40	45,760 (35.9)	19,102 (41.7)	26,658 (58.3)	
41–64	26,052 (20.4)	10,619 (40.8)	15,433 (59.2)	
≥ 65	4,632 (3.6)	1,795 (38.8)	2,837 (61.3)	

Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3)	37,175 (35.8)	66,591 (64.2)	
Female	23,871 (18.7)	7,787 (32.6)	16,084 (67.4)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0)	1,096 (42.4)	1,492 (57.7)	
Car	106,668 (83.6)	37,202 (34.9)	71,342 (66.9)	
Bus/Heavy goods vehicle	18,381 (14.4)	6,664 (36.3)	9,841 (53.5)	
Crash partner's age (years), n (%)				<0.001
≤18	2,415 (1.9)	870 (36.0)	1,545 (64.0)	
19–40	49,103 (38.5)	16,282 (33.2)	32,821 (66.8)	
41–64	35,598 (27.9)	11,736 (33.0)	23,862 (67.0)	
≥65	40,521 (31.8)	16,074 (40.0)	24,447 (60.3)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.6)	35,828 (36.8)	61,619 (63.2)	
Female	30,190 (23.7)	9,134 (30.3)	21,056 (69.7)	

238
239 As shown in Table 3, several variables can contribute to door crashes involving bicycles. Door
240 crashes predominantly occurred in urban areas with speed limits of 20-30 mph (6.2%), while a
241 significantly lower proportion occurred in rural areas with speed limits \geq 40 mph (0.5%). These
242 crashes were overrepresented during non-rush hours (5.5%) and rush hours (4.9%) compared to
243 evening (4.3%) and midnight (2.4%). Cyclists were more frequently involved in door crashes on
244 weekdays (5.4%) than weekends (3.7%). As many as 8.2% of all female cyclists were involved in
245 door crashes, which is higher than the involvement rate among males (4.2%). Taxi and private
246 hire cars were overinvolved in door crashes (10.6%) compared to cars (5.2%) and buses/heavy
247 goods vehicles (3.1%). Crash partners aged \leq 18 years (5.2%) and 19-40 years (5.3%) were
248 disproportionately involved in door crashes compared to older age groups, and female crash
249 partners were overrepresented in door crashes (7.4%) compared to males (4.2%). These results
250 were statistically significant, as indicated by the Chi-squared test ($p < 0.001$). They suggest that
251 various factors—including traffic conditions (rural areas, crash time), cyclist demographics
252 (younger age, female), and characteristics of the crash partner (taxi/private hire cars)—
253 significantly contribute to the likelihood of door crashes involving cyclists.

254 **Table 3.** Distribution of door crashes according to a set of independent variables

Variable	Total (n=127,637)	Door crashes (n=6,363)	Non-door crashes (n=121,274)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3)	5,192 (4.9)	99,861 (95.1)	
Darkness-lit	16,543 (13.0)	1,031 (6.2)	15,512 (93.8)	
Darkness-unlit	6,041 (4.7)	140 (2.3)	5,901 (97.7)	
Speed limit, n (%)				<0.001
Rural (\geq 40 mph)	27,395 (21.5)	123 (0.5)	27,272 (99.6)	
Urban (20–30 mph)	100,242 (78.5)	6,240 (6.2)	94,002 (93.8)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8)	113 (2.4)	4,697 (97.7)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6)	2,056 (4.9)	39,563 (95.1)	
Nonrush hours (09:00–16:00)	61,696 (48.3)	3,363 (5.5%)	58,333 (94.6)	
Evening (19:00–23:00)	19,512 (15.3)	831 (4.3)	18,681 (95.7)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5)	1,072 (3.7)	27,658 (96.3)	
Weekday	98,907 (77.5)	5,291 (5.4)	93,616 (94.7)	
Cyclist's age (years), n (%)				<0.001
\leq 18	51,193 (40.1)	802 (1.6)	50,391 (98.4)	
19–40	45,760 (35.9)	3,474 (7.6)	42,286 (93.4)	
41–64	26,052 (20.4)	1,773 (6.8)	24,279 (93.2)	
\geq 65	4,632 (3.6)	314 (6.8)	4,318 (93.2)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3)	4,404 (4.2)	99,362 (95.8)	
Female	23,871 (18.7)	1,959 (8.2)	21,912 (91.8)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0)	273 (10.6)	2,315 (89.5)	
Car	106,668 (83.6)	5,514 (5.2)	101,154 (94.8)	
Bus/Heavy goods vehicle	18,381 (14.4)	576 (3.1)	17,805 (96.9)	
Crash partner's age (years), n (%)				<0.001
\leq 18	2,415 (1.9)	1,62 (5.2)	2,253 (93.3)	
19–40	49,103 (38.5)	2,585 (5.3)	46,518 (94.7)	
41–64	35,598 (27.9)	1,887 (5.3)	33,711 (94.7)	
\geq 65	40,521 (31.8)	1,729 (4.3)	38,792 (95.7)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.6)	4,123 (4.2)	93,324 (95.8)	
Female	30,190 (23.7)	2,240 (7.4)	27,950 (92.6)	

255

256

257 **Risk factors for the three crash types**

258

259 **Table 4.** Univariate logistic regression results

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Light condition						
Daylight	Ref		Ref		Ref	
Darkness-lit	0.80 (0.77, 0.82)	<0.001	1.11 (1.08, 1.14)	0.036	1.19 (1.17, 1.26)	<0.001
Darkness-unlit	0.93 (0.89, 0.95)	0.001	1.50 (1.46, 1.56)	<0.001	0.74 (0.72, 1.02)	0.198

Speed limit						
Rural (≥40 mph)	Ref		Ref		Ref	
Urban (20–30 mph)	0.40 (0.37, 0.47)	<0.001	0.75 (0.73, 0.79)	<0.001	15.3 (14.6, 18.1)	<0.001
Crash time						
Midnight	1.05 (0.97, 1.10)	0.157	1.34 (1.30, 1.39)	<0.001	0.39 (0.35, 0.47)	<0.001
Rush hours	1.04 (0.98, 1.08)	0.116	1.16 (1.12, 1.20)	0.003	1.36 (1.31, 1.55)	<0.001
Nonrush hours	1.12 (1.06, 1.14)	0.007	1.02 (0.97, 1.13)	0.742	1.78 (1.68, 1.89)	<0.001
Evening	Ref		Ref		Ref	
Crash day						
Weekend	Ref		Ref		Ref	
Weekday	0.92 (0.90, 1.04)	0.341	1.08 (1.07, 1.13)	<0.001	1.33 (1.25, 1.36)	<0.001
Cyclist's age (years)						
≤18	Ref		Ref		Ref	
19–40	1.28 (1.23, 1.39)	<0.001	1.80 (1.76, 1.99)	<0.001	5.26 (5.20, 5.86)	<0.001
41–64	1.47 (1.33, 1.61)	<0.001	1.68 (1.64, 1.81)	<0.001	5.66 (5.47, 6.00)	<0.001
≥65	1.84 (1.78, 1.97)	<0.001	1.54 (1.51, 1.80)	<0.001	5.13 (5.01, 5.83)	<0.001
Cyclist's sex						
Male	Ref		Ref		Ref	
Female	1.14 (1.10, 1.17)	<0.001	0.81 (0.79, 0.91)	<0.001	1.48 (1.33, 1.67)	<0.001
Crash partner						
Taxi/Private hire car	0.63 (0.641, 0.680)	<0.001	1.27 (1.24, 1.334)	<0.001	1.78 (1.46, 1.82)	<0.001
Car	Ref		Ref		Ref	
Bus/HGV	1.31 (1.24, 1.41)	<0.001	1.05 (1.01, 1.15)	<0.001	0.433 (0.40, 0.51)	<0.001
Crash partner's age (years)						
≤18	1.03 (0.97, 1.21)	0.251	1.15 (1.11, 1.34)	<0.001	0.65 (0.62, 0.69)	<0.001
19–40	Ref		Ref		Ref	
41–64	0.93 (0.91, 0.98)	0.035	0.98 (0.97, 1.03)	0.138	0.96 (0.94, 0.99)	<0.001
≥65	2.33 (1.99, 2.56)	<0.001	1.25 (1.20, 1.31)	<0.001	0.51 (0.47, 0.56)	<0.001
Crash partner's sex						
Male	1.28 (1.25, 1.33)	<0.001	1.23 (1.15, 1.39)	<0.001	1.30 (1.25, 1.53)	<0.001
Female	Ref		Ref		Ref	

260 Table 4 presents the results of the univariate logistic regression models. In terms of overtaking
261 crashes, conditions of darkness with lighting (AOR 0.80, 95% CI: 0.77–0.82, $p < 0.001$) and
262 darkness without lighting (AOR 0.93, 95% CI: 0.89–0.95, $p = 0.001$) were linked to a reduced
263 likelihood of crashes when compared to daylight conditions. Urban roads with lower speed limits
264 (20–30 mph) significantly reduced the odds of overtaking crashes compared to rural roads (AOR
265 0.40, 95% CI: 0.37–0.47, $p < 0.001$). In terms of cyclist demographics, older cyclists (≥65 years)
266 were at a notably higher risk (AOR 1.84, 95% CI: 1.78–1.97, $p < 0.001$), and male cyclists were
267 more likely to be involved than female cyclists (AOR 1.14, 95% CI: 1.10–1.17, $p < 0.001$).
268 Additionally, crashes involving buses or heavy goods vehicles (HGVs) increased the likelihood of

269 overtaking crashes (AOR 1.31, 95% CI: 1.24–1.41, $p < 0.001$).

270 For rear-end crashes, both lit (AOR 1.11, 95% CI: 1.08–1.14, $p = 0.036$) and unlit (AOR 1.50,
271 95% CI: 1.46–1.56, $p < 0.001$) darkness conditions were associated with a higher likelihood of
272 crashes compared to daylight. Urban areas were linked to a decreased risk of rear-end crashes
273 compared to rural areas (AOR 0.75, 95% CI: 0.73–0.79, $p < 0.001$). The likelihood of rear-end
274 crashes was significantly higher during midnight (AOR 1.34, 95% CI: 1.30–1.39, $p < 0.001$) and
275 rush hours (AOR 1.16, 95% CI: 1.12–1.20, $p = 0.003$). As with overtaking crashes, older cyclists
276 had an elevated risk (AOR 1.54, 95% CI: 1.51–1.80, $p < 0.001$), while males had slightly reduced
277 odds compared to females (AOR 0.81, 95% CI: 0.79–0.91, $p < 0.001$). Crashes involving buses or
278 heavy goods vehicles were slightly more likely to result in rear-end crashes (AOR 1.05, 95% CI:
279 1.01–1.15, $p < 0.001$).

280 Regarding door crashes, lit conditions during darkness were associated with increased odds of
281 crashes (AOR 1.19, 95% CI: 1.17–1.26, $p < 0.001$), whereas unlit conditions did not show a
282 significant difference compared to daylight (AOR 0.74, 95% CI: 0.72–1.02, $p = 0.198$). Urban
283 environments with lower speed limits were strongly linked to a higher risk of door crashes (AOR
284 15.3, 95% CI: 14.6–18.1, $p < 0.001$). Older cyclists (≥ 65 years) faced a substantially increased risk
285 (AOR 5.13, 95% CI: 5.01–5.83, $p < 0.001$), and male cyclists were more likely to be involved than
286 females (AOR 1.48, 95% CI: 1.33–1.67, $p < 0.001$). Interestingly, crashes involving buses or heavy
287 goods vehicles reduced the likelihood of door crashes compared to cars (AOR 0.433, 95% CI:
288 0.40–0.51, $p < 0.001$).

289
290 **Table 5.** Multivariate logistic regression results
291

Variable	Overtaking crashes	Rear-end crashes	Door crashes
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	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Light condition						
Daylight	Ref		Ref		Ref	
Darkness-lit	0.81 (0.80, 0.84)	<0.001	1.04 (1.00, 1.09)	0.041	1.23 (1.20, 1.24)	<0.001
Darkness-unlit	0.92 (0.90, 0.93)	0.001	1.49 (1.40, 1.57)	<0.001	0.87 (0.86, 1.02)	0.136
Speed limit						
Rural (≥40 mph)	Ref		Ref		Ref	
Urban (20–30 mph)	0.45 (0.43, 0.47)	<0.001	0.76 (0.74, 0.79)	<0.001	16.2 (13.5, 19.4)	<0.001
Crash time						
Midnight	1.07 (0.98, 1.17)	0.119	1.28 (1.21, 1.40)	<0.001	0.50 (0.46, 0.53)	<0.001
Rush hours	1.06 (1.00, 1.12)	0.043	1.12 (1.09, 1.15)	<0.001	1.49 (1.45, 1.62)	<0.001
Nonrush hours	1.09 (1.03, 1.15)	0.003	1.01 (0.96, 1.10)	0.639	1.90 (1.81, 1.93)	<0.001
Evening	Ref		Ref		Ref	
Crash day						
Weekend	Ref		Ref		Ref	
Weekday	0.97 (0.96, 1.01)	0.133	1.09 (1.06, 1.12)	<0.001	1.25 (1.16, 1.34)	<0.001
Cyclist's age (years)						
≤18	Ref		Ref		Ref	
19–40	1.29 (1.24, 1.35)	<0.001	1.84 (1.79, 1.89)	<0.001	5.94 (5.49, 6.44)	<0.001
41–64	1.51 (1.44, 1.58)	<0.001	1.73 (1.68, 1.79)	<0.001	6.13 (5.62, 6.68)	<0.001
≥65	1.79 (1.65, 1.93)	<0.001	1.67 (1.57, 1.78)	<0.001	5.99 (5.22, 6.87)	<0.001
Cyclist's sex						
Male	Ref		Ref		Ref	
Female	1.11 (1.06, 1.15)	<0.001	0.85 (0.83, 0.90)	<0.001	1.68 (1.58, 1.77)	<0.001
Crash partner						
Taxi/Private hire car	0.64 (0.61, 0.69)	<0.001	1.29 (1.19, 1.39)	<0.001	1.61 (1.59, 1.69)	<0.001
Car	Ref		Ref		Ref	
Bus/HGV	1.30 (1.27, 1.33)	<0.001	1.10 (1.06, 1.14)	<0.001	0.48 (0.45, 0.49)	<0.001
Crash partner's age (years)						
≤18	1.10 (0.96, 1.25)	0.162	1.19 (1.17, 1.24)	<0.001	0.65 (0.63, 0.68)	<0.001
19–40	Ref		Ref		Ref	
41–64	0.95 (0.91, 0.99)	0.025	0.96 (0.95, 0.98)	0.026	0.95 (0.93, 0.98)	<0.001
≥65	2.01 (1.94, 2.09)	<0.001	1.20 (1.18, 1.31)	<0.001	0.54 (0.52, 0.57)	<0.001
Crash partner's sex						
Male	1.35 (1.29, 1.42)	<0.001	1.15 (1.12, 1.19)	<0.001	1.37 (1.30, 1.46)	<0.001
Female	Ref		Ref		Ref	

292 Table 5 presents the results of the multivariate logistic regression analysis. In overtaking
293 crashes, the presence of HGVs as partners increases the likelihood by 1.3 times (AOR = 1.30, 95%
294 CI = 1.27–1.33; $p < 0.001$). For cyclists aged 65 and older, the adjusted odds ratio (AOR) is 1.79
295 (95% CI = 1.65–1.93; $p < 0.001$) compared to those aged 18 and younger. Factors associated with
296 a decreased likelihood of crashes include daylight conditions (AOR = 0.81, 95% CI = 0.80–0.84; p
297 < 0.001) and rural areas with speed limits of 40 mph or higher (AOR = 0.45, 95% CI = 0.43–0.47;

298 p < 0.001).

299 For rear-end crashes, significant risk factors included darkness and unlit conditions (AOR =
300 1.49, 95% confidence interval [CI] = 1.40–1.57; p < 0.001), crashes occurring on weekdays (AOR
301 = 1.09, 95% CI = 1.06–1.12; p < 0.001), and an increased likelihood of rear-end crashes during
302 rush hours (AOR = 1.12, 95% CI = 1.09–1.15; p < 0.001). In contrast, the risk is lower in urban
303 areas (AOR = 0.76, 95% CI = 0.74–0.79; p < 0.001) when rural areas are used as the reference.

304 Door crashes are significantly more prevalent in urban areas with speed limits of 20 to 30
305 mph—approximately 16 times higher (AOR = 16.2, 95% CI = 13.5–19.4; p < 0.001). Additionally,
306 interactions with taxis or private hire cars as crash partners further increase the likelihood of
307 these crashes (AOR = 1.61, 95% CI = 1.59–1.69; p < 0.001). Other important risk factors include
308 conditions of darkness with illumination (AOR = 1.23, 95% CI = 1.20–1.24; p < 0.001) and crashes
309 occurring on weekdays (AOR = 1.25, 95% CI = 1.16–1.34; p < 0.001). Furthermore, male crash
310 partners were associated with increased odds of door crashes (AOR = 1.37, 95% CI = 1.30–1.47;
311 p < 0.001).

312
313 Figure 2 presents a forest plot demonstrating the joint effects of several variables on the
314 three crash types when other variables were controlled for. The results identified several key risk
315 factors for both overtaking and rear-end crashes. The risk of overtaking crashes showed a
316 significant increase of 193% in rural areas when elderly drivers were involved (AOR = 2.93, 95%
317 CI = 2.79–3.08), and similarly when heavy goods vehicles (HGVs) were the crash partner (AOR =
318 2.62, 95% CI = 2.46–2.78). Elderly cyclists also faced a higher risk of overtaking crashes on
319 weekends (AOR = 1.56, 95% CI = 1.34–1.81).

320 Regarding rear-end crashes, the risk increased notably with unlit darkness during

321 midnight (AOR = 1.68, 95% CI = 1.48–1.90) and was significantly higher in rural areas (AOR = 2.15,
322 95% CI = 2.01–2.31). Furthermore, bicycling at midnight in rural areas was associated with an
323 increased risk of rear-end crashes (AOR = 1.68; 95% CI = 1.51–1.86). In urban settings, the risk of
324 door crashes was higher for female cyclists (AOR = 2.29; 95% CI = 2.17–2.43) and for elderly
325 cyclists (AOR = 2.06; 95% CI = 1.82–2.34). Finally, female cyclists exhibited a 112% higher
326 likelihood of door crashes when the crash partner was a taxi (AOR = 2.12; 95% CI = 1.68–2.69).

327
328

329 **Discussion**

330 This study explored the relationships among individual and environmental factors in relation
331 to three common bicycle crash types (overtaking, rear-end, and door crashes) on roads in the
332 United Kingdom from 1991 to 2020. The findings revealed several significant factors. First, for
333 overtaking crashes, HGVs as crash partners, rural areas, and the involvement of elderly crash
334 partners emerged as key contributing factors. Second, unlit darkness, midnight hours, and rural
335 areas were the factors most closely associated with rear-end crashes. Third, urban areas and taxis
336 as crash partners significantly increased the likelihood of door crashes. Moreover, male crash
337 partners were found to be a consistent risk factor across all three crash types.

338 Our research findings identified specific risk factors for overtaking crashes, namely rural
339 areas, HGVs as crash partners, and elderly crash partners. These findings align with previous
340 research that identified elderly drivers (23), speeds exceeding 10 mph, and the presence of pick-
341 up trucks as factors contributing to increased risk for overtaking crash. Specifically, HGVs possess
342 several characteristics that amplify this danger. Their large blind spots make it difficult for drivers
343 to see cyclists, increasing the likelihood of crashes during overtaking (24). Additionally, HGVs are

344 less manoeuvrable compared to passenger cars, which reduces their ability to avoid crashes if
345 cyclists suddenly enter their path(25). The speed and distance perception issues between HGVs
346 and cyclists further complicate the judgment of safe overtaking gaps(26). Furthermore, HGVs
347 require longer stopping distances due to their size and weight, which can lead to severe
348 consequences if a sudden need to brake arises. A behavioural study suggested that compared
349 with cars, HGVs tended to maintain a narrower clearance zone when overtaking bicycles (27).
350 Regarding the association with buses or HGVs, Pai et al. suggested that time pressures on HGV
351 drivers for timely loading and unloading might lead to more reckless driving(18). Specifically, our
352 results align with the observations made by Pai et al., who also mentioned higher crash rates
353 involving buses or HGVs, supporting the idea that these time pressures contribute to increased
354 crash risks. Our findings underscore the necessity of implementing measures such as ‘Share the
355 Road’ warning signs (28), particularly in rural settings, where HGVs are likely to execute
356 overtaking manoeuvres at high speed. Such measures could prompt motor vehicles to maintain
357 safer distances from the edges of travel lanes, especially in areas with a notable presence of both
358 HGVs and bicycles.

359 We also identified elderly drivers as a factor contributing to overtaking crashes—a finding
360 consistent with relevant research (23). We found that as individuals age, their risk of being
361 involved in road accidents increases, primarily due to declines in cognitive capabilities. Our study
362 corroborates these findings by showing that older cyclists are more susceptible to accidents
363 during overtaking manoeuvres, which can be attributed to diminished reaction times and
364 impaired decision-making abilities (29), their health (30), and their driving performance (31).
365 Notably, crashes involving elderly individuals often occur in scenarios with challenging conditions,

366 including at intersections without traffic control measures, on high-speed roads, during adverse
367 weather conditions, in poorly lit areas, and in head-on accidents (32-34). The heightened level of
368 risk under such conditions may be attributed to cognitive and perceptual decline in older drivers,
369 which could affect their capacity to execute actions such as overtaking manoeuvres safely.
370 Accordingly, developing specialised cognitive training programmes as interventions to enhance
371 road safety for elderly drivers is evidently necessary (35). Based on our study's findings, we
372 recommend the development of specialised interventions to improve road safety for elderly
373 cyclists. Our analysis reveals that older cyclists are at a higher risk of being involved in overtaking
374 crashes, with this increased risk being strongly linked to declines in cognitive capabilities
375 associated with aging. To address this issue, we advocate for the implementation of targeted
376 cognitive training programs specifically designed for elderly cyclists. These programs should focus
377 on enhancing critical skills such as reaction time, situational awareness, and decision-making
378 abilities, which are crucial for reducing crash risk and improving overall road safety.

379 In the present study, several factors were found to increase the risk of rear-end crashes on
380 road segments, including darkness with unlit surroundings, midnight hours, and rural settings
381 (speed limit > 40 mph). Although few studies have specifically addressed rear-end crashes
382 involving bicycles on road segments, available data suggest that the low conspicuity of bicycles,
383 especially at night, is a recurrent factor in rear-end crashes(18) . Moreover, a lack of adequate
384 street lighting, which is common in rural settings, predisposes cyclists to rear-end crashes. Our
385 joint-effects analysis further indicated that the detrimental effect of unlit darkness is more
386 pronounced in rural areas and during midnight hours. Potential intervention strategies to
387 mitigate rear-end crashes include enhancing illumination and executing speed control

388 management on rural road segments with heavy bicycle traffic.

389 Next, our analysis successfully identified associations of urban areas and taxis and private
390 hire cars as crash partners with door crashes on road segments. Although research specifically
391 focusing on door crashes on road segments is limited, similar findings were documented by Pai,
392 indicating that urban roadways and taxis contributed to door crashes (18). However, determining
393 the factors influencing this trend poses a challenge. One possible explanation could be the
394 increased presence of taxis or private hire cars in such areas, where passengers often disembark.
395 Additionally, our analysis further revealed an elevated risk of door crashes involving crashes with
396 taxis in urban areas. To reduce door crashes on road segments, educating taxi drivers, as well as
397 passengers, about the importance of vigilance when opening doors near traffic is essential (18).
398 In addition, cyclists should be advised to maintain at least a door's width distance from all parked
399 cars to improve the sight triangles of drivers and increase the visibility of cyclists (36).
400 Implementing a two-stage door opening mechanism for vehicles, which would enable drivers to
401 verify the presence of bicycles to the rear, could also be beneficial (37).

402 The strengths of this study include the use of STATS19 datasets spanning from 1991 to 2020,
403 which provides a robust statistical foundation and a broad perspective on trends in bicycle
404 crashes. By focusing specifically on three crash types on road segments—overtaking, rear-end,
405 and door crashes—the study provides a comprehensive and focused analysis, which can yield
406 more actionable insights and more effective recommendations. The UK-based dataset ensures
407 that the findings are particularly relevant for local policy and safety interventions. Additionally,
408 the application of statistical techniques and the consideration of various factors, such as crash
409 partner and time of day, enhance the validity and depth of the analysis.

410 This study had several limitations that warrant acknowledgement. First, the substantial
411 underreporting of nonfatal casualties to the police, particularly casualties involving cyclists not
412 obligated to report accidents, is a critical factor to consider. Such underreporting, as highlighted
413 by the U.K. Government’s Department for Transport (11), likely results in the incomplete
414 representation of nonfatal and ‘slight’ casualties in road casualty data. Second, the STATS19 data
415 utilised in this study lack critical variables, including precrash speeds, specific geometric
416 characteristics of roadways, data regarding alcohol and illicit substance use, and cyclist speed at
417 the time of an accident. Moreover, critical exposure data—such as those related to traffic flow,
418 rider or driver experience, and other elements of risk exposure—are absent, and the absence of
419 such details limits our ability to fully account for potential variations resulting from unobserved
420 factors in the analyses. Finally, this study did not explore annual trends in each type of bicycle
421 crash over the 30-year study period; investigating such trends could provide insights regarding
422 changing behaviours among cyclists and motor vehicle drivers as well as the effects of legislative
423 changes for road speed limits.

424 One inherent problem with police-reported crash data is the variables not readily available,
425 hereby causing unobserved heterogeneity across the observations. To overcome such a
426 limitation, we estimated separate regression models, as suggested by Kim et al.(38), for the three
427 crash types; such an approach provides greater explanatory power compared to single overall
428 models. Further, we conducted joint-effect analyses of several variables of interest that capture
429 heterogeneity. In our previous studies, we adopted the above-mentioned approaches to
430 overcome the inherent problem with a success (39, 40).

431 Future research directions could involve integrating GPS (Global Positioning System) data

432 and weather conditions to analyse both injury frequency and fatalities of bicycle crashes on road
433 segments. Additionally, exploring the potential of autonomous vehicles for detecting
434 approaching bicycles for door-crashes and implementing AI-controlled lighting systems in rural
435 areas for cyclist detection could be promising areas for further study.

436

437 **Recommendations**

438 For overtaking crashes, we recommend implementing 'Share the Road' warning signs,
439 especially in rural areas, and developing specialized cognitive training programs for elderly
440 drivers. Regarding rear-end crashes, our suggestions include improving illumination during night
441 time and implementing speed control measures on rural road segments. For door crashes
442 involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility.
443 Moreover, implementing a two-stage door opening mechanism and an automatic detection
444 device in vehicles to alert drivers of bicycles approaching from behind could potentially be
445 beneficial.

446

447 **Conclusions**

448 This study identified several significant risk factors for the three predominate types of crashes
449 involving cyclists on road segments: HGVs as crash partners, elderly crash partners, and rural
450 areas for overtaking crashes; unlit darkness, midnight hours, and rural areas for rear-end crashes;
451 and urban areas and taxis as crash partners for door crashes. These risk factors remained
452 unchanged since our previous study conducted in 2011(18). The present research enhances the
453 field of bicycle safety research by concluding that the detrimental effects of certain variables

454 become more pronounced under certain conditions. For example, first, cyclists in rural settings
455 exhibited an elevated risk of overtaking crashes involving HGVs. Second, the rear-end crash risk
456 increases in the combined presence of unlit darkness, midnight hours, and rural areas. Finally, in
457 urban settings, the likelihood of door crashes increases when a taxi is the crash partner.

458

459 **Abbreviations**

460 WHO: World Health Organization; HGVs: heavy goods vehicles; AOR: adjusted odds ratio; CI:
461 confidence interval.

462

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465

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469 **Data merging and analysis:** Akhmad Fajri Widodo, Wafaa Saleh, Bayu Satria Wiratama.

470 **Writing - original draft:** Chun-Chieh Chao.

471 **Writing – review and editing:** Hui-An Lin, Chenyi Chen, Hon-Ping Ma, Akhmad Fajri Widodo
472 Cheng-Wei Chan,.

473 **Validation:** Chun-Chieh Chao, Hui-An Lin, Chenyi Chen, Hon-Ping Ma, Shih Yu Ko.

474 **Supervision:** Li Wei, Yen-Nung Lin, Shou-Chien Hsu, Chih-Wei Pai.

475

476

477

478 **Availability of data and materials**

479 This study utilised the British STATS19 database, which contains data on all road traffic accidents

480 in the United Kingdom. The data that support the findings of this study are openly available at

481 <https://figshare.com/ndownloader/files/48173452>.

482

483 **Declarations**

484 **Ethical approval and consent to participate**

485 This study was conducted in accordance with the Declaration of Helsinki and approved by the

486 Joint Institutional Review Board of Taipei Medical University (N202011030).

487

488 **Consent for publication**

489 This study was approved by the Joint Institutional Review Board of Taipei Medical

490 University (N202011030). The Joint Institutional Review Board of Taipei Medical University has

491 waived the requirement of informed consent. All methods were performed in accordance with

492 the relevant guidelines and regulations of the Declaration of Helsinki.

493

494 **Competing interests**

495 The authors declare that they have no competing interests in relation to this work.

496

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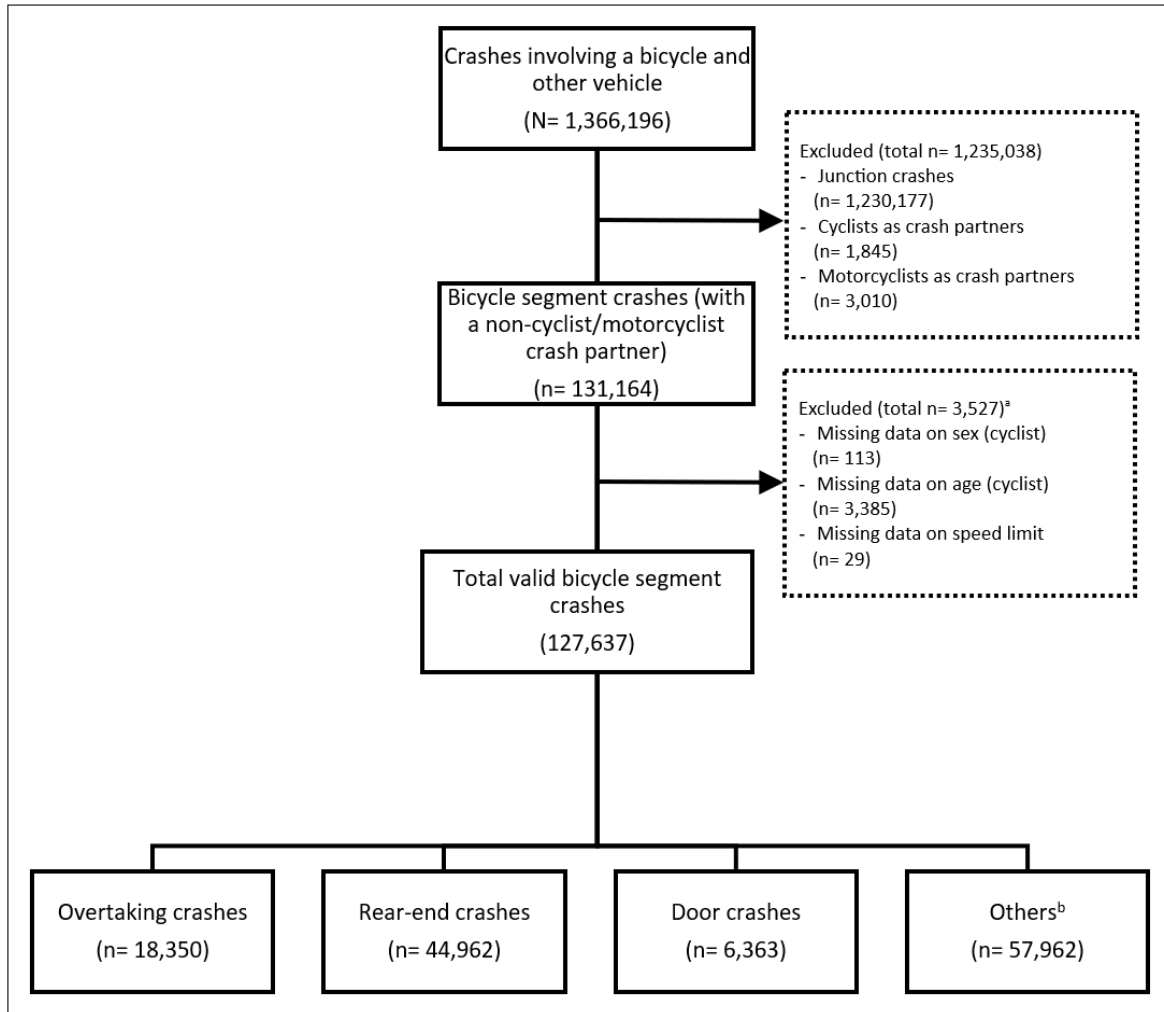


Fig. 1. Flowchart of the study sample selection process. ^aListed excluded criteria are nonexclusive; thus, the sum of the total may exceed 3,527. ^bOther crashes include reversing crashes and head-on crashes.

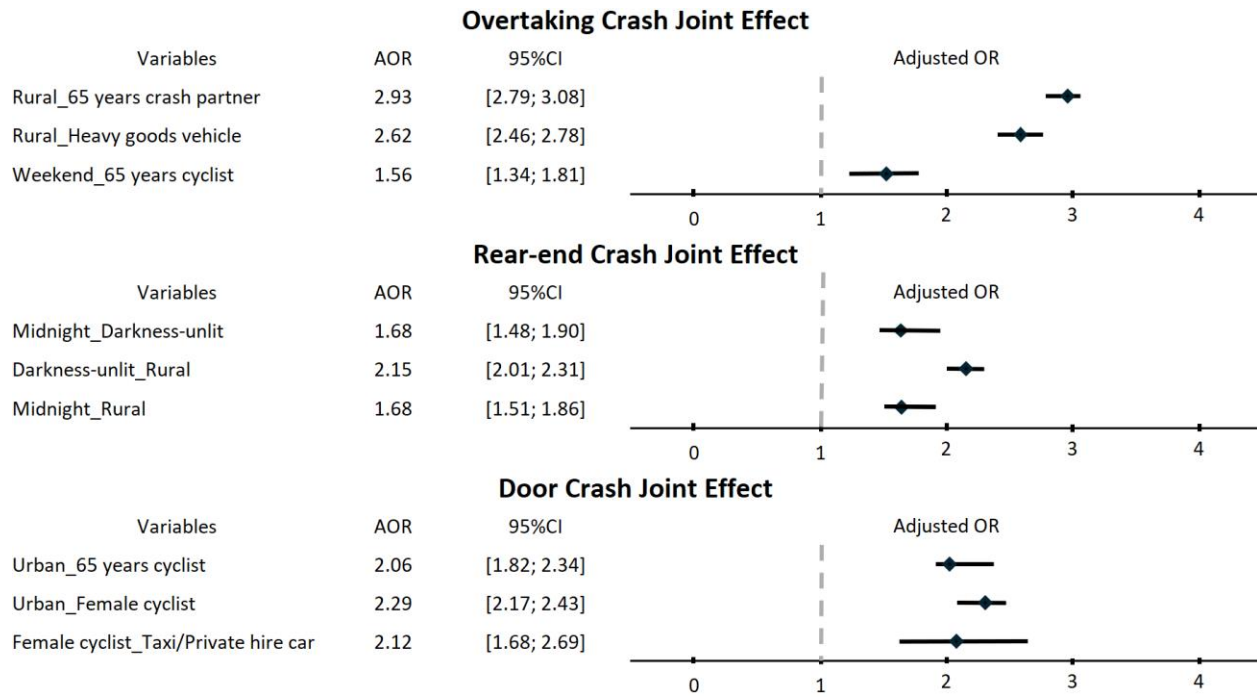


Fig. 2. Joint effects of several variables on the three crash types.

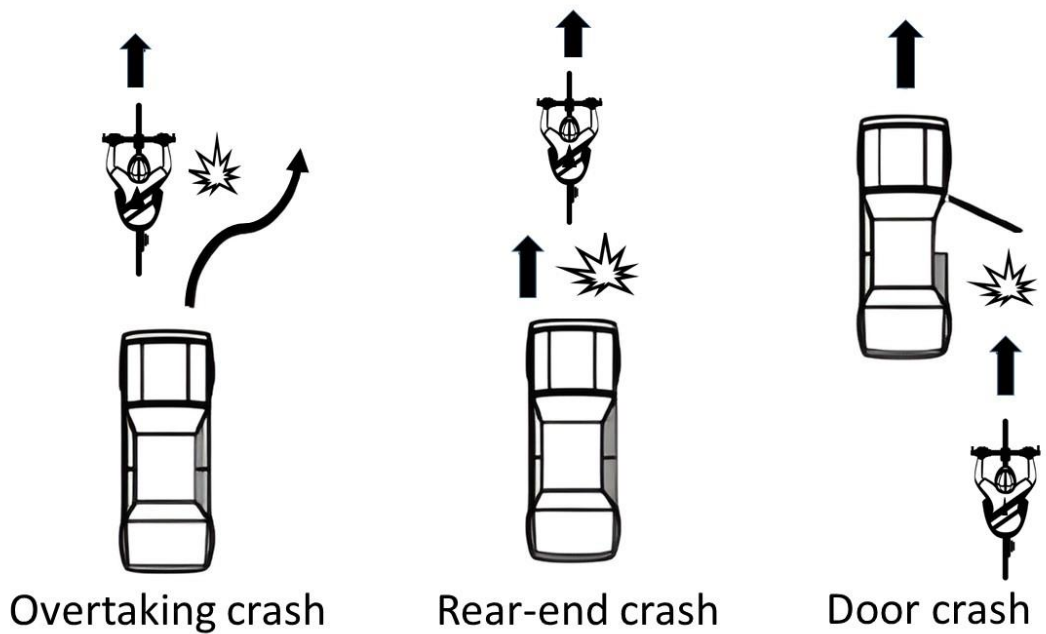


Figure 2. Illustrative diagram of the three crash types

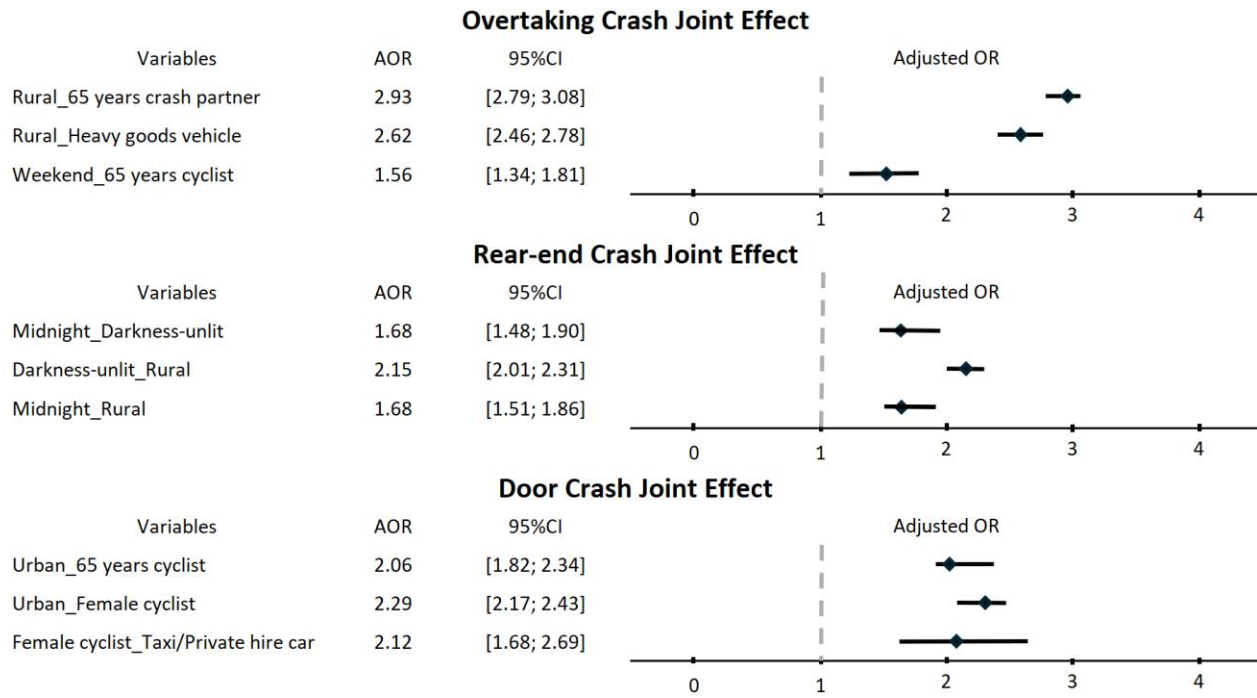


Fig. 3. Joint effects of several variables on the three crash types.

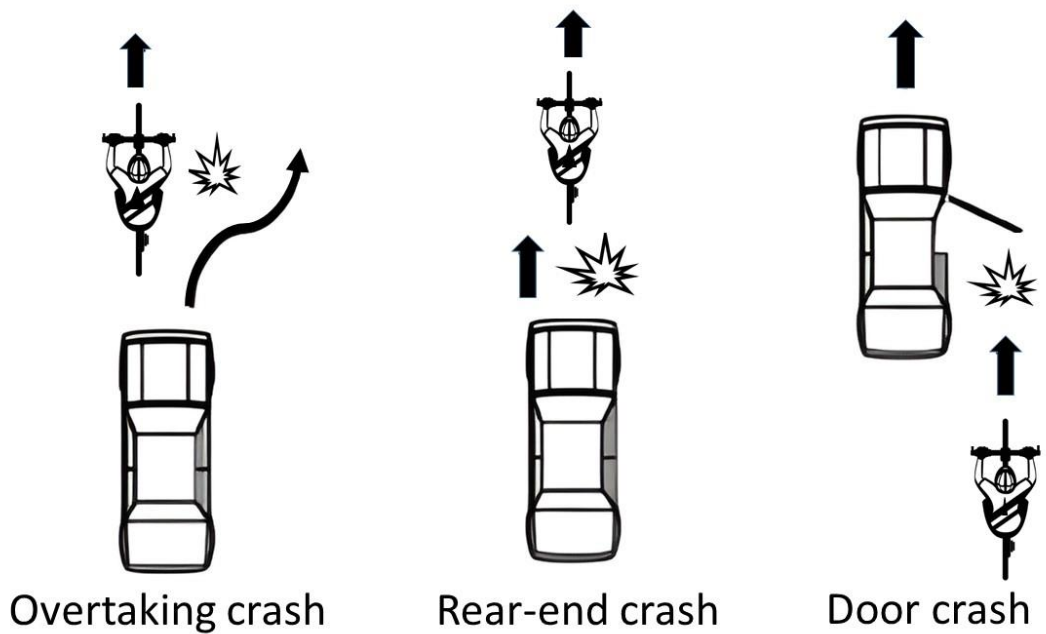


Figure 2. Illustrative diagram of the three crash types

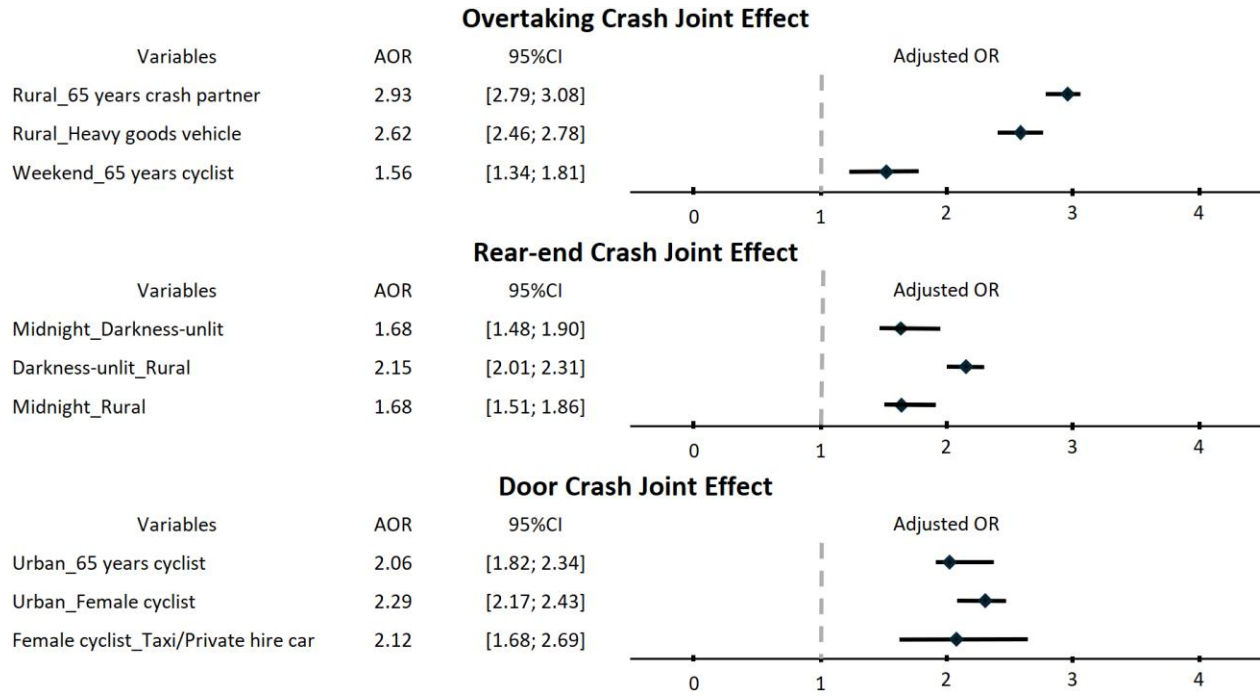


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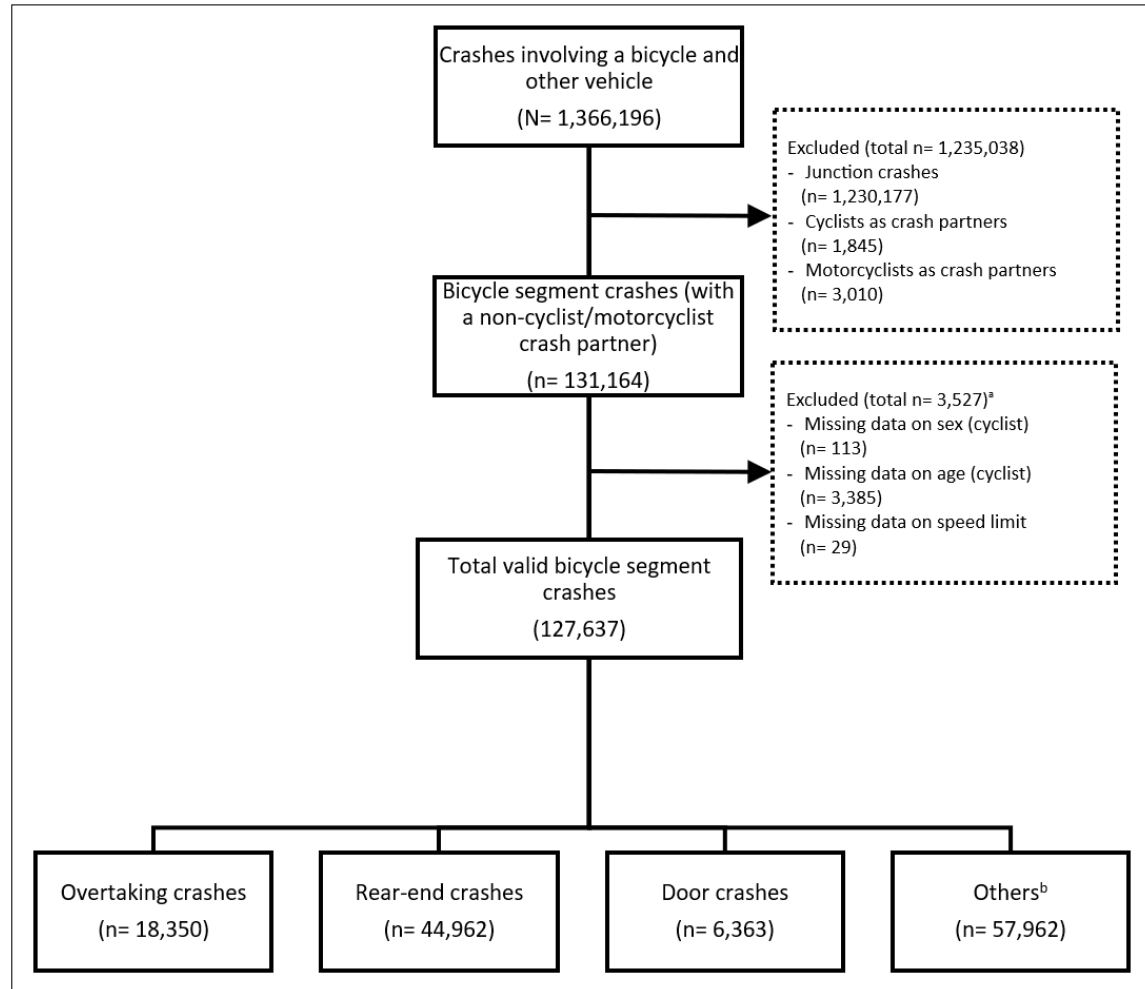


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1 **Risk Factors for Overtaking, Rear-End, and Door Crashes Involving Bicycles in the United**
2 **Kingdom: Revisited and Reanalysed**
3

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1

22 Abstract

23 **Background:** Relevant research has provided valuable insights into risk factors for bicycle crashes
24 at intersections. However, few studies have focused explicitly on three common types of bicycle
25 crashes on road segments: overtaking, rear-end, and door crashes.

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26 **Objective:** This study aims to identify risk factors for overtaking, rear-end, and door crashes that
27 occur on road segment.

28 Material and methods

29 ~~The current study examined the risk factors associated with these three types of crashes~~
30 ~~occurring on road segments.~~ We analysed British STATS19 accident records from 1991 to 2020.

31 Using multivariate logistic regression models, we estimated adjusted odds ratios (AORs) with 95%
32 confidence intervals (CIs) for multiple risk factors. The analysis included 127,637 bicycle crashes,
33 categorised into 18,350 overtaking, 44,962 rear-end, 6,363 door, and 57,962 other crashes.

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34 Results

35 Significant risk factors for overtaking crashes included speed limits of ≥ 40 miles per hour (mph)
36 (AOR = 2.238, 95% CI = 2.159–2.320), heavy goods vehicles (HGVs) as crash partners (AOR = 2.867,
37 95% CI 2.473–3.323), and elderly crash partners (AOR = 2.013, 95% CI = 1.937–2.092). For rear-
38 end crashes, noteworthy risk factors included unlit darkness (AOR = 1.486, 95% CI = 1.404–1.573)
39 and midnight hours (AOR = 1.269, 95% CI = 1.190–1.354). Factors associated with door crashes
40 included speed limits of 20–30 mph (AOR = 16.185, 95% CI = 13.514–19.382) and taxi and private
41 hire cars (AOR = 2.695, 95% CI = 2.310–3.145). Our joint-effect analysis revealed additional
42 interesting results; for example, there were elevated risks for overtaking crashes in rural areas
43 with elderly drivers as crash partners (AOR = 2.93, 95% CI = 2.79–3.08) and with HGVs as crash

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44 partners (AOR = 2.62, 95% CI = 2.46–2.78).

45

46 **Conclusions**

47 The aforementioned risk factors remained largely unchanged since 2011, when we conducted
48 our previous study. However, the present study concluded that the detrimental effects of certain
49 variables became more pronounced in certain situations. For example, cyclists in rural settings
50 exhibited an elevated risk of overtaking crashes involving HGVs as crash partners.

51

52 **Keywords:** Bicycle crash; Road segment; Overtaking crash; Rear-end crash; Door crash

53

54

55 **Introduction**

56 In recent years, urban bicycling has become increasingly popular in many countries, offering
57 benefits such as reduced traffic congestion, diminished parking pressure, and a reduction in
58 greenhouse gas emissions [1, 2]. The World Health Organization has highlighted numerous health
59 advantages of moderate-intensity physical activities such as bicycling, including improvements in
60 life expectancy, quality of life, cognitive function, mental health, sleep quality, muscular and
61 cardiorespiratory fitness, and bone and functional health [2].

62 However, despite such health benefits, the risk of injury remains a considerable safety
63 concern for cyclists, who are regarded as vulnerable road users [2, 3]. Traffic crash data indicate
64 that the risk of accidents for cyclists, measured per distance travelled, is approximately 20 times
65 higher than that for vehicle drivers[2]. To address this problem, researchers in the United States

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66 developed a comprehensive bicycle route safety rating model with a focus on injury severity [4].
67 This model evaluates multiple operational and physical aspects such as traffic volume, population
68 density, highway classification, lane width, and the presence of one-way streets. In addition, it is
69 capable of predicting the severity of injuries due to motor vehicle–related crashes at specific
70 locations [4]. Another finding was that a route is considered adequately safe if it includes
71 geometric factors that enhance safety [4]. This model can aid urban planners and public officials
72 in creating infrastructure such as bike lanes and implementing strict lane policies to improve
73 cyclist safety [4]. Implementing bike lanes has been demonstrated to reduce crash rates by up to
74 40% among adult cyclists [5]. One study regarding roundabouts indicated that roundabouts with
75 cycle tracks significantly reduced injury risk for cyclists compared with those lacking bicycle
76 infrastructure [6]. Furthermore, adequate night-time lighting on rural roads has the potential to
77 prevent over half of all cyclist injuries [7]. Bicycle crashes can also impose a significant burden on
78 healthcare expenses. Elvik and Sundfør [8] have discussed the economic implications and
79 healthcare expenditures associated with bicycle accidents. For instance, in Belgium, the average
80 cost of bicycle accidents per case is estimated at 841 euros [9]. In the Netherlands, the total
81 annual cost has been reported as €410.7 million [10].

82 Although intersectional crashes are generally more frequent than nonintersectional ones, in
83 2020, 64% of fatal crashes involving cyclists occurred on road segments, defined as areas 20 m
84 away from intersections, whereas only 26% of such fatalities occurred at intersections [11]. Bil et
85 al. demonstrated that car drivers, when at fault for crashes, often cause more serious
86 consequences for cyclists on straight road sections [12]. In crashes occurring on road segments,
87 several factors contribute to high injury severity, including being in a rural region with an elevated

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88 speed limit, male gender, and cyclist age of >55 years [13]. Another identified risk factor is
89 bicycling on roads against oncoming traffic [14].

90 Although relevant research has shed light on risk factors for bicycle crashes at intersections,
91 few studies have explicitly investigated crashes on road segments. Bicycle crashes on road
92 segments remain a substantial issue for public health concern. Existing research primarily
93 emphasizes intersection-related crashes. This study aims to fill a critical gap by conducting a
94 thorough examination of the risk factors associated with three distinct bicycle crash types:
95 overtaking, rear-end, and door crashes that occur on road segments. Studies that have examined
96 bicycle crashes relatively broadly, without distinguishing crash types, have identified several key
97 factors—including vehicle volume [15], traffic density [16], number of lanes [16], access points
98 along road segments [15], shoulder and median widths [15], parking space availability [15, 16] ,
99 length of continuous two-way left-turn lanes [15], and pavement type [17]—all of which
100 contribute to bicycle crashes on road segments. Several studies have specifically explored
101 overtaking, rear end, and door crashes involving bicycles. The primary objective of this study,
102 building on our previous research, two exceptional work have examined into risk factors related
103 to for overtaking, rear-end, and door crashes, is to conduct a more comprehensive investigation.
104 [18, 19]. Specifically, Pai identified buses and coaches as common crash partners in overtaking
105 crashes, poor visibility, traversing manoeuvres, and teenage cyclists as risk factors for rear-end
106 crashes, and built-up areas as a risk factor for door crashes [18]. In addition, another study linked
107 the speed of a passing vehicle to increased severity of cyclist injury in overtaking crashes [19].

108 The primary objective of the present study, an extension of our previous study [18], was to
109 analyse police-reported crash data from additional years to determine whether the risk factors

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110 for these three crash types remained unchanged. The study addresses a critical gap in current
111 research, focusing on crashes specifically occurring on road segments. Existing literature offers
112 limited insights into ~~this specific type of crash~~ these crash types, highlighting a crucial need for
113 targeted investigations. These crashes have the potential for severe impacts, involving complex
114 dynamics that demand a nuanced understanding for effective mitigation strategies. By exploring
115 these factors, our research aims to significantly enhance cyclist safety within this particular
116 context. Furthermore, we aimed to untangle the joint associations of several factors—including
117 light conditions, urban versus rural settings, vehicle types, and rider and driver characteristics—
118 with these three crash types.

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119

120 **Material and Methods**

121 **Crash data source**

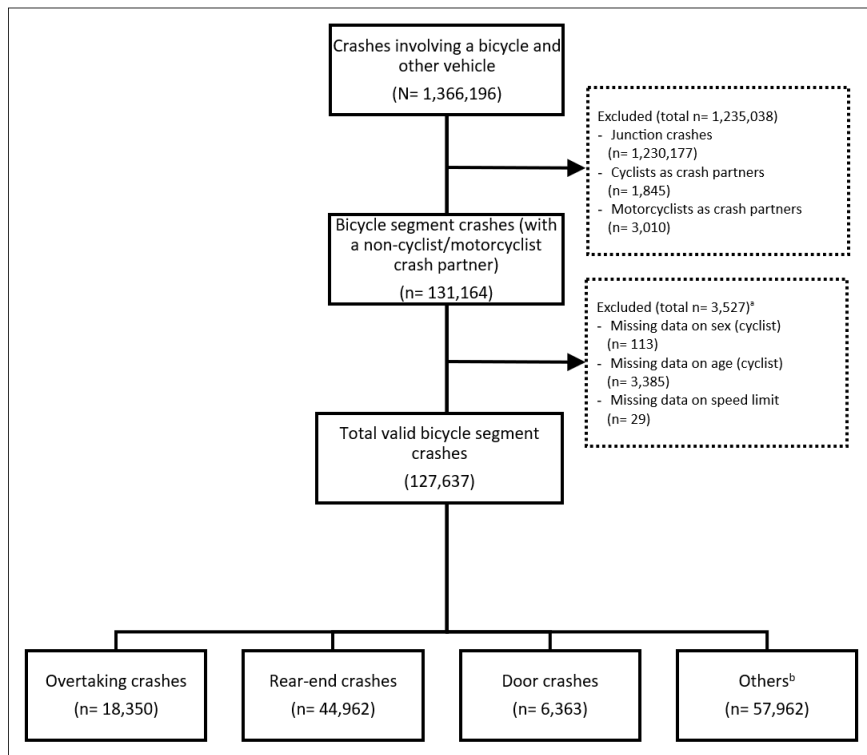
122 The present investigation utilised data from 01/01/1991 to 31/12/2020, obtained from the
123 United Kingdom's official road traffic casualty database, STATS19. Police record such data either
124 at crash scenes or within 30 days of each crash. The UK's Department for Transport compiles the
125 data, which the United Kingdom Data Archive then maintains and distributes. The dataset
126 encompasses a variety of variables, including crash circumstances (e.g., time and date, weather
127 conditions, road and light conditions, posted speed limit, road type), vehicle and driver
128 characteristics, demographic details of the drivers, precrash manoeuvres of the vehicles, and the
129 initial impact point of the vehicle. Additionally, the dataset contains demographic information
130 and details regarding injury severity for each casualty. This study adhered to the STROBE
131 (strengthening the reporting of observational studies in epidemiology) reporting guidelines. [20]

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132 Injury severity in the aforementioned dataset is divided into three categories, namely slight,
133 serious, and fatal. Fatal injuries refer to those leading to death within 30 days of the accident.
134 Serious injuries include conditions such as fractures, internal injuries, severe cuts and lacerations,
135 concussions, and any injury requiring hospitalisation. Slight injuries include sprains, bruises, and
136 minor cuts, as well as mild shock requiring roadside attention. The exclusive focus of this study
137 was crashes leading to cyclist casualties.

138 As shown in Figure 1, this study analysed 1,366,196 crashes involving bicycles and other
139 vehicles. Initially, 1,235,032 junction cases were excluded. From the remaining 131,164 bicycle
140 segment crashes, 3,527 were further excluded because of incomplete demographic data for the
141 cyclist and missing speed limit information, leaving a valid cohort of 127,637 bicycle segment
142 crashes for analysis. Within this cohort, this study identified 18,350 overtaking crashes, 44,962
143 rear-end crashes, 6,363 door crashes, and 57,962 other types of crashes.

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144

145 **Figure 1.** Flowchart of the study sample selection process. ^aListed excluded criteria are nonexclusive; thus, the
 146 sum of the total may exceed 3,527. ^bOther crashes include reversing crashes and head-on crashes.

147

148 **Classification of crash types**

149 As shown in [Figure 2](#), an overtaking crash is defined as a crash where a motorised vehicle
 150 overtakes and impacts with a bicycle, which may be travelling straight, overtaking another vehicle,
 151 changing lanes, or turning. A rear-end crash occurs when a following vehicle impacts with the
 152 rear of a bicycle. A door crash involves a bicycle either being struck by or striking the opening
 153 door of an automobile. These three crash types were described using schematics in our previous
 154 study [18].

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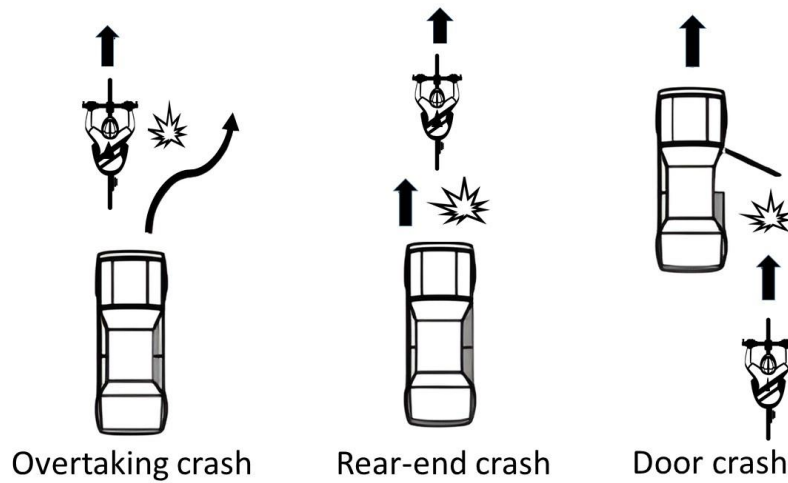


Figure 2. Illustrative diagram of the three crash types

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Data collection

For the present study, the three crash types of focus (overtaking, rear-end, and door crashes) were the binary-dependent variables. The collected data encompassed the following factors: lighting conditions on the roadway at the time of the crash (daylight, darkness-lit, darkness-unlit), the speed limit at the crash scene (rural: ≥ 40 miles per hour [mph]; urban: 20–30 mph), the time of day categorised into four periods according to traffic volume (midnight: 00:00–06:00; rush hours: 07:00–08:00 and 17:00–18:00; nonrush hours: 09:00–16:00; and evening: 19:00–23:00), and the day of the week (weekday or weekend day). The demographic details of cyclist casualties encompassed age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex (male or female). Finally, the demographic details of the crash partner included the type of vehicle (identified as a taxi, private hire car, car, bus, or heavy goods vehicle [HGV]), age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex (male or female). On a cautionary note, we removed junction cases to avoid the variability

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189 estimated, and X_1, X_2, \dots, X_p represent the predictor variables.

190 Before estimating the model, assumptions of logistic regression, such as linearity of the logit,
191 absence of multicollinearity, and independence of observations, were evaluated. An odds ratio
192 (OR) greater than 1 indicated a positive association between the independent variable and the
193 occurrence rate, while an OR less than 1 indicated a negative association. An OR of 1 suggested
194 no association between the variables of interest and the outcomes. All statistical analyses were
195 conducted using SPSS Statistics version 25 for Windows (IBM Corp., Armonk, New York, USA). A
196 p value lower than 0.05 in two-tailed tests was considered statistically significant.

197

198 **Results**

199 **Population characteristics**

200 Tables 1, 2, and 3 present the distributions of overtaking, rear-end, and door crashes, respectively,
201 in relation to multiple independent variables. These data revealed that a significant proportion
202 of bicycle crashes occurred in daylight (82.3%), occurred in urban settings (78.5%), occurred
203 during nonrush hours (48.3%), occurred on weekdays (77.5%), involved cyclists aged under 18
204 years (40.1%), and involved male cyclists (81.3%). Additionally, most crashes involved cars as
205 crash partners (83.6%), and crash partners were predominately aged 19–40 years (38.5%) and
206 were male (76.4%). Table 1 highlights an overrepresentation in bicycle overtaking crashes for
207 certain variables, namely unlit darkness (19.5%), rural areas (24.8%), midnight hours (17.7%),
208 buses or HGVs as crash partners (24.7%), and elderly crash partners (21.5%) and male crash
209 partners (16.0%). These results were revealed to be statistically significant by the chi-squared

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210 test ($p < 0.01$).

211

212 **Table 1.** Distribution of overtaking crashes according to a set of independent variables

Variable	Total (n=127,637)	Overtaking crashes (n=18,350)	Non-overtaking crashes (n=109,287)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	15,283 (14.55%)	89,770 (85.5%)	
Darkness-lit	16,543 (13.0%)	1,889 (11.42%)	14,654 (88.6%)	
Darkness-unlit	6,041 (4.7%)	1,178 (19.50%)	4,863 (80.5%)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5%)	6,805 (24.8%)	20,590 (75.6%)	
Urban (20–30 mph)	100,242 (78.5%)	11,545 (11.5%)	88,697 (88.5%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	852 (17.7%)	3,958 (82.3%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	5,685 (13.7%)	35,934 (86.3%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	9,386 (15.2%)	52,310 (84.8%)	
Evening (19:00–23:00)	19,512 (15.3%)	2,427 (12.4%)	17,085 (87.6%)	
Crash day, n (%)				0.094
Weekend	28,730 (22.5%)	4,218 (14.7%)	24,512 (85.2%)	
Weekday	98,907 (77.5%)	14,132 (14.3%)	84,775 (85.7%)	
Cyclist's age (years), n (%)				<0.001
≤ 18	51,193 (40.1%)	5,220 (10.2%)	45,973 (89.8%)	
19–40	45,760 (35.9%)	7,108 (15.5%)	38,652 (84.5%)	
41–64	26,052 (20.4%)	5,012 (19.2%)	21,040 (80.8%)	
≥ 65	4,632 (3.6%)	1,010 (21.8%)	3,622 (78.2%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	14,746 (14.2%)	89,020 (85.8%)	
Female	23,871 (18.7%)	3,604 (15.1%)	20,267 (84.9%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	208 (8.0%)	2,380 (92.0%)	
Car	106,668 (83.6%)	13,599 (12.8%)	93,069 (87.3%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	4,543 (24.7%)	13,838 (75.3%)	
Crash partner's age (years), n (%)				<0.001
≤ 18	2,415 (1.9%)	281 (11.6%)	2,134 (88.4%)	
19–40	49,103 (38.5%)	5,398 (11.0%)	43,705 (89.0%)	
41–64	35,598 (27.9%)	3,973 (11.2%)	31,625 (88.8%)	
≥ 65	40,521 (31.8%)	8,698 (21.5%)	31,823 (78.5%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.4%)	15,584 (16.0%)	81,863 (84.0%)	
Female	30,190 (23.8%)	2,766 (9.2%)	27,424 (90.8%)	

213

214 Several variables in Table 2 reveal significant differences between rear-end crashes and non-
215 rear-end crashes. Specifically, a higher proportion of rear-end crashes occurred under darkness-
216 unlit conditions (50.2%) compared to darkness-lit conditions (37.5%). Additionally, rear-end
217 crashes were more prevalent in rural areas with speed limits of ≥ 40 mph (43.0%) compared to

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218 urban areas with speed limits of 20–30 mph (33.1%). Crashes involving crash partners aged ≥ 65
 219 accounted for 39.7% of rear-end crashes, which was higher compared to other age groups (age
 220 41–64: 33.0% and ≤18: 36.0%). Furthermore, rear-end crashes were more likely to occur during
 221 midnight (47.6%) compared to rush hours (36.3%). Taxis were frequently involved in rear-end
 222 crashes (42.4%), as were male crash partners (36.8%). These findings highlight the significant
 223 influence of various factors on the likelihood of rear-end crashes. Variables such as darkness-unlit
 224 conditions, higher speed limits in rural areas, crash time, and characteristics of the crash partner
 225 all emerged as significant determinants. Specifically, rear-end crashes were notably more
 226 prevalent under darkness-unlit conditions, in rural areas with higher speed limits, during
 227 midnight hours, and involving certain characteristics of crash partners. Importantly, these
 228 associations were statistically significant, as indicated by the Chi-squared test ($p < 0.001$).

230 **Table 2.** Distribution of rear-end crashes according to a set of independent variables

Variable	Total (n=127,637)	Rear-end crashes (n=44,962)	Non-rear-end crashes (n=82,675)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	35,726 (34.1%)	69,333 (66.0%)	
Darkness-lit	16,543 (13.0%)	6,204 (37.5%)	10,339 (63.5%)	
Darkness-unlit	6,041 (4.73%)	3,032 (50.19%)	3,003 (49.71%)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5%)	11,788 (43.0%)	15,607 (57.0%)	
Urban (20–30 mph)	100,242 (78.5%)	33,174 (33.1%)	67,068 (66.9%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	2,289 (47.6%)	2,521 (52.4%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	15,089 (36.3%)	26,530 (63.7%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	20,723 (33.6%)	40,973 (66.4%)	
Evening (19:00–23:00)	19,512 (15.3%)	6,861 (36.2%)	12,651 (64.9%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5%)	9,485 (33.0%)	19,245 (67.0%)	
Weekday	98,907 (77.5%)	35,477 (35.9%)	63,430 (64.1%)	
Cyclist's age (years), n (%)				<0.001
≤18	51,193 (40.1%)	13,446 (26.3%)	37,747 (73.7%)	
19–40	45,760 (35.9%)	19,102 (41.7%)	26,658 (58.3%)	
41–64	26,052 (20.4%)	10,619 (40.8%)	15,433 (59.2%)	
≥65	4,632 (3.6%)	1,795 (38.8%)	2,837 (61.3%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	37,175 (35.8%)	66,591 (64.2%)	
Female	23,871 (18.7%)	7,787 (32.6%)	16,084 (67.4%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	1,096 (42.4%)	1,492 (57.7%)	
Car	106,668 (83.6%)	37,202 (34.9%)	71,342 (66.9%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	6,664 (36.3%)	9,841 (53.5%)	
Crash partner's age (years), n (%)				<0.001
≤18	2,415 (1.9%)	870 (36.0%)	1,545 (64.0%)	
19–40	49,103 (38.5%)	16,282 (33.2%)	32,821 (66.8%)	
41–64	35,598 (27.9%)	11,736 (33.0%)	23,862 (67.0%)	
≥65	40,521 (31.8%)	16,074 (40.0%)	24,447 (60.3%)	
Crash partner's sex, n (%)				<0.001

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Male	97,447 (76.6%)	35,828 (36.8%)	61,619 (63.2%)
Female	30,190 (23.7%)	9,134 (30.3%)	21,056 (69.7%)

231
232 As shown in Table 3, several variables can contribute to door crashes involving bicycles. Door
233 crashes predominantly occurred in urban areas with speed limits of 20-30 mph (6.2%), while a
234 significantly lower proportion occurred in rural areas with speed limits \geq 40 mph (0.5%). These
235 crashes were overrepresented during non-rush hours (5.5%) and rush hours (4.9%) compared to
236 evening (4.3%) and midnight (2.4%). Cyclists were more frequently involved in door crashes on
237 weekdays (5.4%) than weekends (3.7%). As many as 8.2% of all female cyclists were involved in
238 door crashes, which is higher than the involvement rate among males (4.2%). Taxi and private
239 hire cars were overinvolved in door crashes (10.6%) compared to cars (5.2%) and buses/heavy
240 goods vehicles (3.1%). Crash partners aged \leq 18 years (5.2%) and 19-40 years (5.3%) were
241 disproportionately involved in door crashes compared to older age groups, and female crash
242 partners were overrepresented in door crashes (7.4%) compared to males (4.2%). These results
243 were statistically significant, as indicated by the Chi-squared test ($p < 0.001$). They suggest that
244 various factors—including traffic conditions (rural areas, crash time), cyclist demographics
245 (younger age, gender), and characteristics of the crash partner (taxi/private hire cars)—
246 significantly contribute to the likelihood of door crashes involving cyclists.

247 **Table 3.** Distribution of door crashes according to a set of independent variables

Variable	Total (n=127,637)	Door crashes (n=6,363)	Non-door crashes (n=121,274)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	5,192 (4.9%)	99,861 (95.1%)	
Darkness-lit	16,543 (13.0%)	1,031 (6.2%)	15,512 (93.8%)	
Darkness-unlit	6,041 (4.7%)	140 (2.3%)	5,901 (97.7%)	
Speed limit, n (%)				<0.001
Rural (\geq 40 mph)	27,395 (21.5%)	123 (0.5%)	27,272 (99.6%)	
Urban (20–30 mph)	100,242 (78.5%)	6,240 (6.2%)	94,002 (93.8%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	113 (2.4%)	4,697 (97.7%)	

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Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	2,056 (4.9%)	39,563 (95.1%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	3,363 (5.5%)	58,333 (94.6%)	
Evening (19:00–23:00)	19,512 (15.3%)	831 (4.3%)	18,681 (95.7%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5%)	1,072 (3.7%)	27,658 (96.3%)	
Weekday	98,907 (77.5%)	5,291 (5.4%)	93,616 (94.7%)	
Cyclist's age (years), n (%)				<0.001
≤18	51,193 (40.1%)	802 (1.6%)	50,391 (98.4%)	
19–40	45,760 (35.9%)	3,474 (7.6%)	42,286 (93.4%)	
41–64	26,052 (20.4%)	1,773 (6.8%)	24,279 (93.2%)	
≥65	4,632 (3.6%)	314 (6.8%)	4,318 (93.2%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	4,404 (4.2%)	99,362 (95.8%)	
Female	23,871 (18.7%)	1,959 (8.2%)	21,912 (91.8%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	273 (10.6%)	2,315 (89.5%)	
Car	106,668 (83.6%)	5,514 (5.2%)	101,154 (94.8%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	576 (3.1%)	17,805 (96.9%)	
Crash partner's age (years), n (%)				<0.001
≤18	2,415 (1.9%)	1,62 (5.2%)	2,253 (93.3%)	
19–40	49,103 (38.5%)	2,585 (5.3%)	46,518 (94.7%)	
41–64	35,598 (27.9%)	1,887 (5.3%)	33,711 (94.7%)	
≥65	40,521 (31.8%)	1,729 (4.3%)	38,792 (95.7%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.6%)	4,123 (4.2%)	93,324 (95.8%)	
Female	30,190 (23.7%)	2,240 (7.4%)	27,950 (92.6%)	

248

249

250 Risk factors for the three crash types

251 Table 4 presents the logistic regression model results. Regarding overtaking crashes, the
 252 identified risk factors included daylight conditions (adjusted odds ratio [AOR] = 1.233, 95%
 253 confidence interval [CI] = 1.162–1.309; $p < 0.001$), speed limits of ≥ 40 mph (AOR = 2.238, 95% CI
 254 = 2.159–2.320; $p < 0.001$), nonrush hours (AOR = 1.091, 95% CI 1.031–1.154; $p = 0.003$), cyclists
 255 aged ≥ 65 years (AOR = 1.785, 95% CI = 1.649–1.931; $p < 0.001$), female cyclists (AOR = 1.106, 95%
 256 CI = 1.062–1.153), HGVs as crash partners (AOR = 2.867, 95% CI = 2.473–3.323; $p < 0.001$), elderly
 257 crash partners (AOR = 2.013, 95% CI = 1.937–2.092; $p < 0.001$), and male crash partners (AOR =
 258 1.353, 95% CI = 1.292–1.416; $p < 0.001$).

259 For rear-end crashes, noteworthy risk factors included unlit darkness (AOR = 1.486, 95% CI

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260 = 1.404–1.573; $p < 0.001$), speed limits of ≥ 40 mph (AOR = 1.315, 95% CI = 1.277–1.354; $p < 0.001$),
 261 weekdays (AOR = 1.090, 95% CI = 1.059–1.122; $p < 0.001$), midnight hours (AOR = 1.269, 95% CI =
 262 1.190–1.354; $p < 0.001$), and taxis as crash partners (AOR = 1.286, 95% CI = 1.186–1.394; $p < 0.001$).

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263 Regarding door crashes, significant risk factors included lit darkness (AOR = 1.373, 95% CI =
 264 1.141–1.651; $p < 0.001$), speed limits of 20–30 mph (AOR = 16.185, 95% CI = 13.514–19.382;
 265 $p < 0.001$), weekdays (AOR = 1.246, 95% CI = 1.162–1.336; $p < 0.001$), and nonrush hours (AOR =
 266 2.912, 95% CI = 2.384–3.556; $p < 0.001$). Additionally, female cyclists (AOR = 1.675, 95% CI = 1.582–
 267 1.774; $p < 0.001$), taxis or private hire cars as crash partners (AOR = 2.695, 95% CI = 2.310–3.145;
 268 $p < 0.001$), male crash partners (AOR = 1.373, 95% CI = 1.296–1.455; $p < 0.001$), and crash partners
 269 aged 41–64 years (AOR = 1.855, 95% CI = 1.625–2.117; $p < 0.001$) were associated with door
 270 crashes.

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278 **Table 4.** Multivariate logistic regression results

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	<i>p</i> value	AOR (95% CI)	<i>p</i> value	AOR (95% CI)	<i>p</i> value
Light condition						
Daylight	1.233 (1.162, 1.309)	<0.001	Ref		1.146 (0.958, 1.370)	0.137
Darkness-lit	Ref		1.042 (1.002, 1.085)	0.041	1.373 (1.141, 1.651)	0.001
Darkness-unlit	1.152 (1.059, 1.253)	0.001	1.486 (1.404, 1.573)	<0.001	Ref	
Speed limit						
Rural (≥ 40 mph)	2.238 (2.159, 2.320)	<0.001	1.315 (1.277, 1.354)	<0.001	Ref	
Urban (20–30 mph)	Ref		Ref		16.185 (13.514, 19.382)	<0.001
Crash time						
Midnight	1.073 (0.982, 1.173)	0.119	1.269 (1.190, 1.354)	<0.001	Ref	
Rush hours	1.059 (1.002, 1.120)	0.043	1.108 (1.078, 1.139)	<0.001	2.502 (2.051, 3.052)	<0.001
Nonrush hours	1.091 (1.031, 1.154)	0.003	Ref		2.912 (2.384, 3.556)	<0.001
Evening	Ref		0.992 (0.953, 1.032)	0.686	2.014 (1.646, 2.465)	<0.001

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Table 4. Multivariate logistic regression results (*continued*)

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Crash day						
Weekend	1.031 (0.991, 1.072)	0.132	Ref		Ref	
Weekday	Ref		1.090 (1.059, 1.122)	<0.001	1.246 (1.162, 1.336)	<0.001
Cyclist's age (years)						
≤18	Ref		Ref		Ref	
19–40	1.292 (1.242, 1.345)	<0.001	1.839 (1.788, 1.891)	<0.001	5.943 (5.489, 6.435)	<0.001
41–64	1.509 (1.444, 1.578)	<0.001	1.731 (1.676, 1.789)	<0.001	6.129 (5.621, 6.684)	<0.001
≥65	1.785 (1.649, 1.931)	<0.001	1.671 (1.568, 1.780)	<0.001	5.988 (5.217, 6.874)	<0.001
Cyclist's sex						
Male	Ref		1.172 (1.137, 1.208)	<0.001	Ref	
Female	1.106 (1.062, 1.153)	<0.001	Ref		1.675 (1.582, 1.774)	<0.001
Crash partner						
Taxi/Private hire car	Ref		1.286 (1.186, 1.394)	<0.001	2.695 (2.310, 3.145)	<0.001
Car	1.571 (1.359, 1.816)	<0.001	Ref		2.089 (1.908, 2.286)	<0.001
Bus/Heavy goods vehicle	2.867 (2.473, 3.323)	<0.001	1.099 (1.061, 1.139)	<0.001	Ref	
Crash partner's age (years)						
≤18	1.097 (0.963, 1.249)	0.162	1.225 (1.188, 1.263)	<0.001	1.507 (1.313, 1.731)	<0.001
19–40	Ref		1.038 (1.008, 1.069)	0.013	1.855 (1.625, 2.117)	<0.001
41–64	0.950 (0.909, 0.994)	0.025	Ref		1.801 (1.574, 2.060)	<0.001
≥65	2.013 (1.937, 2.092)	<0.001	1.241 (1.137, 1.355)	<0.001	Ref	
Crash partner's sex						
Male	1.353 (1.292, 1.416)	<0.001	1.150 (1.117, 1.185)	<0.001	1.373 (1.296, 1.455)	<0.001
Female	Ref		Ref		Ref	

279
 280 Figure 2 presents a forest plot demonstrating the joint effects of several variables on the
 281 three crash types when other variables were controlled for. The results identified several key risk

282 factors for both overtaking and rear-end crashes. The risk of overtaking crashes showed a
 283 significant increase of 193% in rural areas when elderly drivers were involved (AOR = 2.93, 95%
 284 CI = 2.79–3.08), and similarly when heavy goods vehicles (HGVs) were the crash partner (AOR =
 285 2.62, 95% CI = 2.46–2.78). Elderly cyclists also faced a higher risk of overtaking crashes on
 286 weekends (AOR = 1.56, 95% CI = 1.34–1.81).

287 Regarding rear-end crashes, the risk increased notably with unlit darkness during
 288 midnight (AOR = 1.68, 95% CI = 1.48–1.90) and was significantly higher in rural areas (AOR = 2.15,

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289 95% CI = 2.01–2.31). Furthermore, bicycling at midnight in rural areas was associated with an
 290 increased risk of rear-end crashes (AOR = 1.68; 95% CI = 1.51–1.86). In urban settings, the risk of
 291 door crashes was higher for female cyclists (AOR = 2.29; 95% CI = 2.17–2.43) and for elderly
 292 cyclists (AOR = 2.06; 95% CI = 1.82–2.34). Finally, female cyclists exhibited a 112% higher
 293 likelihood of door crashes when the crash partner was a taxi (AOR = 2.12; 95% CI = 1.68–2.69).

294

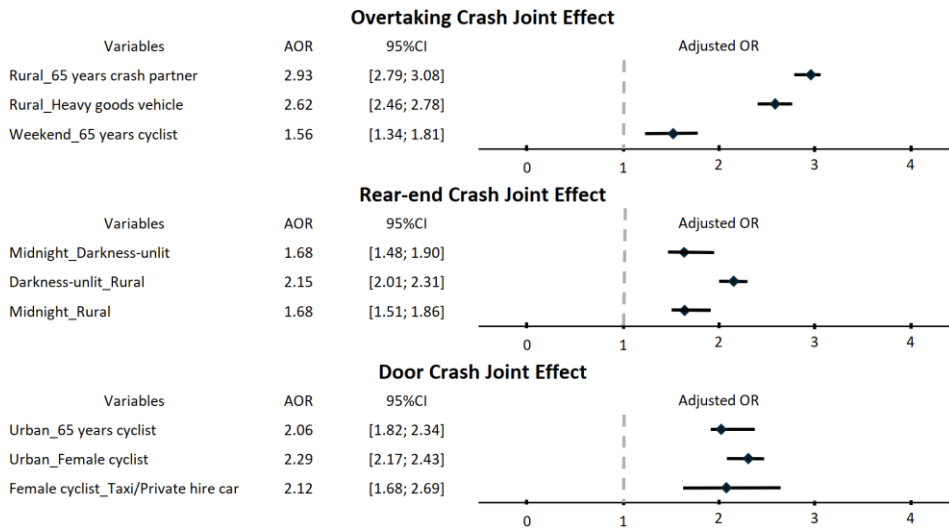


Figure 3. Joint effects of several variables on the three crash types.

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301 Discussion

302 This study explored the relationships among individual and environmental factors in relation to
 303 three common bicycle crash types (overtaking, rear-end, and door crashes) on roads in the United
 304 Kingdom from 1991 to 2020. The findings revealed several significant factors. First, for overtaking
 305 crashes, HGVs as crash partners, rural areas, and the involvement of elderly crash partners

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306 emerged as key contributing factors. Second, unlit darkness, midnight hours, and rural areas
307 were the factors most closely associated with rear-end crashes. Third, urban areas and taxis as
308 crash partners significantly increased the likelihood of door crashes. Moreover, male crash
309 partners were found to be a consistent risk factor across all three crash types.

310 Our research findings identified specific risk factors for overtaking crashes, namely rural
311 areas, HGVs as crash partners, and elderly crash partners. These findings align with previous
312 research that identified elderly drivers [24], speeds exceeding 10 mph, and the presence of pick-
313 up trucks as factors contributing to increased risk for overtaking crash. Specifically, HGVs possess
314 several characteristics that amplify this danger. Their large blind spots make it difficult for drivers
315 to see cyclists, increasing the likelihood of crashes during overtaking. Additionally, HGVs are less
316 maneuverable compared to passenger cars, which reduces their ability to avoid
317 crashes if cyclists suddenly enter their path. The speed and distance perception issues between
318 HGVs and cyclists further complicate the judgment of safe overtaking gaps. Furthermore, HGVs
319 require longer stopping distances due to their size and weight, which can lead to severe
320 consequences if a sudden need to brake arises. A behavioural study suggested that compared
321 with cars, HGVs tended to maintain a narrower clearance zone when overtaking bicycles [25].

322 Regarding the association with buses or HGVs, Pai et al. [18], ~~suggests~~ suggested that time
323 pressures on HGV drivers for timely loading and unloading might lead to more reckless driving.
324 Specifically, our results align with the observations made by Pai et al., who also mentioned higher
325 crash rates involving buses or HGVs, supporting the idea that these time pressures contribute to
326 increased crash risks. Our findings underscore the necessity of implementing measures such as
327 'Share the Road' warning signs [26], particularly in rural settings, where HGVs are likely to execute

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328 overtaking manoeuvres at high speed. Such measures could prompt motor vehicles to maintain
329 safer distances from the edges of travel lanes, especially in areas with a notable presence of both
330 HGVs and bicycles.

331 We also identified elderly drivers as a factor contributing to overtaking crashes—a finding
332 consistent with relevant research [24]. We found that as individuals age, their risk of being
333 involved in road accidents increases, primarily due to declines in cognitive capabilities. Our study
334 corroborates these findings by showing that older cyclists are more susceptible to accidents
335 during overtaking ~~maneuvers~~manoeuvres, which can be attributed to diminished reaction times
336 and impaired decision-making abilities [27], their health [28], and their driving performance [29].

337 Notably, crashes involving elderly individuals often occur in scenarios with challenging conditions,
338 including at intersections without traffic control measures, on high-speed roads, during adverse
339 weather conditions, in poorly lit areas, and in head-on accidents [30-32]. The heightened level of
340 risk under such conditions may be attributed to cognitive and perceptual decline in older drivers,
341 which could affect their capacity to execute actions such as overtaking manoeuvres safely.
342 Accordingly, developing specialised cognitive training programmes as interventions to enhance

343 road safety for elderly drivers is evidently necessary [33]. Based on our study's findings, we
344 recommend the development of ~~specialized~~specialised interventions to improve road safety for
345 elderly cyclists. Our analysis reveals that older cyclists are at a higher risk of being involved in
346 overtaking crashes, with this increased risk being strongly linked to declines in cognitive
347 capabilities associated with aging. To address this issue, we advocate for the implementation of
348 targeted cognitive training programs specifically designed for elderly cyclists. These programs
349 should focus on enhancing critical skills such as reaction time, situational awareness, and

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350 decision-making abilities, which are crucial for reducing crash risk and improving overall road
351 safety.

352 In the present study, several factors were found to increase the risk of rear-end crashes on
353 road segments, including darkness with unlit surroundings, midnight hours, and rural settings
354 (speed limit > 40 mph). Although few studies have specifically addressed rear-end crashes
355 involving bicycles on road segments, available data suggest that the low conspicuity of bicycles,
356 especially at night, is a recurrent factor in rear-end crashes [18, 34]. Moreover, a lack of adequate
357 street lighting, which is common in rural settings, predisposes cyclists to rear-end crashes [18].
358 Our joint-effects analysis further indicated that the detrimental effect of unlit darkness is more
359 pronounced in rural areas and during midnight hours. Potential intervention strategies to
360 mitigate rear-end crashes include enhancing illumination and executing speed control
361 management on rural road segments with heavy bicycle traffic.

362 Next, our analysis successfully identified associations of urban areas and taxis and private
363 hire cars as crash partners with door crashes on road segments. Although research specifically
364 focusing on door crashes on road segments is limited, similar findings were documented by Pai,
365 indicating that urban roadways and taxis contributed to door crashes [18]. However, determining
366 the factors influencing this trend poses a challenge. One possible explanation could be the
367 increased presence of taxis or private hire cars in such areas, where passengers often disembark.
368 Additionally, our analysis further revealed an elevated risk of door crashes involving crashes with
369 taxis in urban areas. To reduce door crashes on road segments, educating taxi drivers, as well as
370 passengers, about the importance of vigilance when opening doors near traffic is essential [18].
371 In addition, cyclists should be advised to maintain at least a door's width distance from all parked

372 cars to improve the sight triangles of drivers and increase the visibility of cyclists [35].
373 Implementing a two-stage door opening mechanism for vehicles, which would enable drivers to
374 verify the presence of bicycles to the rear, could also be beneficial [36].

375 The strengths of this study include the use of STATS19 datasets spanning from 1991 to 2020,
376 which provides a robust statistical foundation and a broad perspective on trends in bicycle
377 crashes. By focusing specifically on three crash types on road segments—overtaking, rear-end,
378 and door crashes—the study provides a comprehensive and focused analysis, which can yield
379 more actionable insights and more effective recommendations. The UK-based dataset ensures
380 that the findings are particularly relevant for local policy and safety interventions. Additionally,
381 the application of statistical techniques and the consideration of various factors, such as crash
382 partner and time of day, enhance the validity and depth of the analysis.

383 This study had several limitations that warrant acknowledgement. First, the substantial
384 underreporting of nonfatal casualties to the police, particularly casualties involving cyclists not
385 obligated to report accidents, is a critical factor to consider. Such underreporting, as highlighted
386 by the U.K. Government’s Department for Transport [11], likely results in the incomplete
387 representation of nonfatal and ‘slight’ casualties in road casualty data. Second, the STATS19 data
388 utilised in this study lack critical variables, including precrash speeds, specific geometric
389 characteristics of roadways, data regarding alcohol and illicit substance use, and cyclist speed at
390 the time of an accident. Moreover, critical exposure data—such as those related to traffic flow,
391 rider or driver experience, and other elements of risk exposure—are absent, and the absence of
392 such details limits our ability to fully account for potential variations resulting from unobserved
393 factors in the analyses. Finally, this study did not explore annual trends in each type of bicycle

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394 crash over the 30-year study period; investigating such trends could provide insights regarding
395 changing behaviours among cyclists and motor vehicle drivers as well as the effects of legislative
396 changes for road speed limits.

397 One inherent problem with police-reported crash data is the variables not readily available,
398 hereby causing unobserved heterogeneity across the observations. To overcome such a
399 limitation, we estimated separate regression models, as suggested by Kim et al. [37], for the three
400 crash types; such an approach provides greater explanatory power compared to single overall
401 models. Further, we conducted joint-effect analyses of several variables of interest that capture
402 heterogeneity. In our previous studies, we adopted the above-mentioned approaches to
403 overcome the inherent problem with a success [38, 39].

404 Future research directions could involve integrating GPS (Global Positioning System) data
405 and weather conditions to analyse both ~~the~~ injury frequency and fatalities of bicycle crashes on
406 road segments. Additionally, exploring the potential of autonomous vehicles for detecting
407 approaching bicycles for door-crashes and implementing AI-controlled lighting systems in rural
408 areas for cyclist detection could be promising areas for further study.

410 **Recommendations**

411 For overtaking crashes, we recommend implementing 'Share the Road' warning signs,
412 especially in rural areas, and developing specialized cognitive training programs for elderly
413 drivers. Regarding rear-end crashes, our suggestions include improving illumination during night
414 time and implementing speed control measures on rural road segments. For door crashes
415 involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility.

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416 Moreover, implementing a two-stage door opening mechanism and an automatic detection
417 device in vehicles to alert drivers of bicycles approaching from behind could potentially be
418 beneficial.

419

420 **Conclusions**

421 This study identified several significant risk factors for the three predominate types of crashes
422 involving cyclists on road segments: HGVs as crash partners, elderly crash partners, and rural
423 areas for overtaking crashes; unlit darkness, midnight hours, and rural areas for rear-end crashes;
424 and urban areas and taxis as crash partners for door crashes. These risk factors remained
425 unchanged since our previous study conducted in 2011 [15]. The present research enhances the
426 field of bicycle safety research by concluding that the detrimental effects of certain variables
427 become more pronounced under certain conditions. For example, first, cyclists in rural settings
428 exhibited an elevated risk of overtaking crashes involving HGVs. Second, the rear-end crash risk
429 increases in the combined presence of unlit darkness, midnight hours, and rural areas. Finally, in
430 urban settings, the likelihood of door crashes increases when a taxi is the crash partner.

431

432 **Abbreviations**

433 WHO: World Health Organization; HGVs: heavy goods vehicles; AOR: adjusted odds ratio; CI:
434 confidence interval.

435

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438

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454 interpretation of data, or preparation of the manuscript.

455

456 **Availability of data and materials**

457 This study utilised the British STATS19 database, which contains data on all road traffic accidents
458 in the United Kingdom. The data that support the findings of this study are openly available at

459 <https://figshare.com/ndownloader/files/48173452https://www.data.gov.uk/dataset/cb7ae6f0-4bc6-4935-9277-47c5ce24a11f/road-safety-data>.

461

462 **Declarations**

463 **Ethical approval and consent to participate**

464 This study was conducted in accordance with the Declaration of Helsinki and approved by the
465 Joint Institutional Review Board of Taipei Medical University (N202011030).

466

467 **Consent for publication**

468 This study was approved by the Joint Institutional Review Board of Taipei Medical
469 University (N202011030). The Joint Institutional Review Board of Taipei Medical University has
470 waived the requirement of informed consent. All methods were performed in accordance with
471 the relevant guidelines and regulations of the Declaration of Helsinki.

472

473 **Competing interests**

474 The authors declare that they have no competing interests in relation to this work.

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1 **Risk Factors for Overtaking, Rear-End, and Door Crashes Involving Bicycles in the United**
2 **Kingdom: Revisited and Reanalysed**
3

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22 **Abstract**

23 **Background and** ~~Relevant research has provided valuable insights into risk factors for bicycle~~
24 ~~crashes at intersections. However, few studies have focused explicitly on three common types of~~
25 ~~bicycle crashes on road segments: overtaking, rear-end, and door crashes.~~

26 **Objective:** ~~Relevant research has provided valuable insights into risk factors for bicycle crashes~~
27 ~~at intersections. However, few studies have focused explicitly on three common types of bicycle~~
28 ~~crashes on road segments: overtaking, rear-end, and door crashes. This study aims to identify~~
29 ~~risk factors for overtaking, rear-end, and door crashes that occur on road segment. Relevant~~
30 ~~research has provided valuable insights into risk factors for bicycle crashes at intersections.~~
31 ~~However, few studies have focused explicitly on three common types of bicycle crashes on road~~
32 ~~segments: overtaking, rear-end, and door crashes. This study aims to identify risk factors for~~
33 ~~overtaking, rear-end, and door crashes that occur on road segments.~~

34 **Material and methods**

35 We analysed British STATS19 accident records from 1991 to 2020. Using multivariate logistic
36 regression models, we estimated adjusted odds ratios (AORs) with 95% confidence intervals (CIs)
37 for multiple risk factors. The analysis included 127,637 bicycle crashes, categorised into 18,350
38 overtaking, 44,962 rear-end, 6,363 door, and 57,962 other crashes.

39 **Results**

40 Significant risk factors for overtaking crashes included ~~speed limits of ≥ 40 miles per hour (mph)~~
41 ~~(AOR = 2.2438, 95% CI = 2.1596–2.320)~~, heavy goods vehicles (HGVs) as crash partners (AOR =
42 ~~1.302–867~~, 95% CI ~~2.41.273–3.321.333~~), and elderly crash partners (AOR = ~~2.012–013~~, 95% CI =
43 ~~1.94–2.091–9374–2.092~~), and decreased risk in rural area with speed limits of 20-30 miles per

44 [hour](#) (AOR = 0.45, 95% CI =0.43-0.47). For rear-end crashes, noteworthy risk factors included
45 unlit darkness (AOR = 1.4869, 95% CI = 1.404–1.573) and midnight hours (AOR = 1.26978, 95% CI
46 = 1.19210–1.40354). Factors associated with door crashes included [urban areas speed limits of](#)
47 [20–30 mph](#) (AOR = 16.21859, 95% CI = 13.514–19.4382) and taxi ~~or~~ private hire cars (AOR =
48 ~~2.6957~~[01.61](#), 95% CI =~~1.57–2.310–3.14~~[51.69](#)). Our joint-effect analysis revealed additional
49 interesting results; for example, there were elevated risks for overtaking crashes in rural areas
50 with elderly drivers as crash partners (AOR = 2.93, 95% CI = 2.79–3.08) and with HGVs as crash
51 partners (AOR = 2.62, 95% CI = 2.46–2.78).

52

53 **Conclusions**

54 The aforementioned risk factors remained largely unchanged since 2011, when we conducted
55 our previous study. However, the present study concluded that the detrimental effects of certain
56 variables became more pronounced in certain situations. For example, cyclists in rural settings
57 exhibited an elevated risk of overtaking crashes involving HGVs as crash partners.

58

59 **Keywords:** Bicycle crash; Road segment; Overtaking crash; Rear-end crash; Door crash

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63 **Introduction**

64 In recent years, urban bicycling has become increasingly popular in many countries, offering
65 benefits such as reduced traffic congestion, diminished parking pressure, and a reduction in

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66 greenhouse gas emissions (1, 2). The World Health Organization has highlighted numerous health
67 advantages of moderate-intensity physical activities such as bicycling, including improvements in
68 life expectancy, quality of life, cognitive function, mental health, sleep quality, muscular and
69 cardiorespiratory fitness, and bone and functional health (1).

70 However, despite such health benefits, the risk of injury remains a considerable safety
71 concern for cyclists, who are regarded as vulnerable road users (1, 3). Traffic crash data indicate
72 that the risk of accidents for cyclists, measured per distance travelled, is approximately 20 times
73 higher than that for vehicle drivers(1). To address this problem, researchers in the United States
74 developed a comprehensive bicycle route safety rating model with a focus on injury severity (4).
75 This model evaluates multiple operational and physical aspects such as traffic volume, population
76 density, highway classification, lane width, and the presence of one-way streets. In addition, it is
77 capable of predicting the severity of injuries due to motor vehicle–related crashes at specific
78 locations (4). Another finding was that a route is considered adequately safe if it includes
79 geometric factors that enhance safety (4). This model can aid urban planners and public officials
80 in creating infrastructure such as bike lanes and implementing strict lane policies to improve
81 cyclist safety (4). Implementing bike lanes has been demonstrated to reduce crash rates by up to
82 40% among adult cyclists (5). One study found that roundabouts with dedicated cycle tracks
83 significantly lower the risk of injury for cyclists compared to those without such bicycle
84 infrastructure. One study regarding roundabouts indicated that roundabouts with cycle tracks
85 significantly reduced injury risk for cyclists compared with those lacking bicycle infrastructure (6).
86 Furthermore, adequate night-time lighting on rural roads has the potential to prevent over half
87 of all cyclist injuries (7). Bicycle crashes can also impose a significant burden on healthcare

88 expenses. Elvik and Sundfør (8) have discussed the economic implications and healthcare
89 expenditures associated with bicycle accidents. For instance, in Belgium, the average cost of
90 bicycle accidents per case is estimated at 841 euros (9). In the Netherlands, the total annual cost
91 has been reported as €410.7 million (10).

92 Although intersectional crashes are generally more frequent than non-intersectional ones, in
93 2020, 64% of fatal crashes involving cyclists occurred on road segments, defined as areas 20
94 meters away from intersections, whereas only 26% of such fatalities occurred at intersections
95 (11). Bil et al. demonstrated that car drivers, when at fault for crashes, often cause more serious
96 consequences for cyclists on straight road sections (12). In crashes occurring on road segments,
97 several factors contribute to high injury severity, including being in a rural region with an elevated
98 speed limit, male gender, and cyclist age of >55 years (13). Another identified risk factor is
99 bicycling on roads against oncoming traffic (14).

100 Although relevant research has shed light on risk factors for bicycle crashes at intersections,
101 few studies have explicitly investigated crashes on road segments. Bicycle crashes on road
102 segments remain a substantial issue for public health concern. This study aims to fill a critical gap
103 by conducting a thorough examination of the risk factors associated with three distinct bicycle
104 crash types: overtaking, rear-end, and door crashes that occur on road segments. Studies that
105 have examined bicycle crashes relatively broadly, without distinguishing crash types, have
106 identified several key factors—including vehicle volume (15), traffic density (16), number of lanes
107 (16), access points along road segments (15), shoulder and median widths (15), parking space
108 availability (15, 16), length of continuous two-way left-turn lanes (15), and pavement type (17)—
109 all of which contribute to bicycle crashes on road segments. [One notable study has examined the](#)

110 ~~risk factors for overtaking, rear-end, and door crashes~~ ~~Two exceptional work have examined risk~~
111 ~~factors for overtaking, rear end, and door crashes~~ (18). Specifically, Pai identified buses and
112 coaches as common crash partners in overtaking crashes, poor visibility, traversing manoeuvres,
113 and teenage cyclists as risk factors for rear-end crashes, and built-up areas as a risk factor for
114 door crashes(18) . In addition, another study linked the speed of a passing vehicle to increased
115 severity of cyclist injury in overtaking crashes (19). The high mortality rate from crashes on
116 road segments underscores the significant risks linked to overtaking, rear-end, and door
117 crashes. Overtaking, involving high-speed maneuvers, greatly increases the likelihood of
118 severe accidents. Rear-end crashes, frequently triggered by sudden stops or aggressive
119 tailgating, pose a persistent threat to cyclists. Furthermore, injuries sustained by cyclists
120 striking an opening car door can be devastating due to the impacts from the door, ground, or
121 vehicles behind. These critical issues highlight the urgent need for identifying risk factors for
122 these crashes. The high mortality rate from crashes on road segments underscores the significant
123 risks linked to overtaking, rear end collisions, and door crashes. Overtaking, involving high speed
124 maneuvers, greatly increases the likelihood of severe accidents. Rear end collisions, frequently
125 triggered by sudden stops or aggressive tailgating, pose a persistent threat to cyclists.
126 Furthermore, door crashes introduce serious hazards in already dangerous conditions. These
127 critical issues highlight the urgent need for substantial improvements in road design, driving
128 practices, and safety features to effectively mitigate these risks.

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129 The primary objective of the present study, an extension of our previous ~~study, study,~~ was to
130 analyse police-reported crash data from additional years to determine whether the risk factors
131 for these three crash types remained unchanged. The study addresses a critical gap in current

132 research, focusing on crashes specifically occurring on road segments. Existing literature offers
133 limited insights into these crash types, highlighting a crucial need for targeted investigations.
134 These crashes have the potential for severe impacts, involving complex dynamics that demand a
135 nuanced understanding for effective mitigation strategies. By exploring these factors, our
136 research aims to significantly enhance cyclist safety within this particular context. Furthermore,
137 we aimed to untangle the joint associations of several factors—including light conditions, urban
138 versus rural settings, vehicle types, and rider and driver characteristics—with these three crash
139 types.

140

141 **Material and Methods**

142 **Crash data source**

143 The present investigation utilised data from 01/01/1991 to 31/12/2020, obtained from the
144 United Kingdom’s official road traffic casualty database, STATS19. Police record such data either
145 at crash scenes or within 30 days of each crash. The UK’s Department for Transport compiles the
146 data, which the United Kingdom Data Archive then maintains and distributes. The dataset
147 encompasses a variety of variables, including crash circumstances (e.g., time and date, weather
148 conditions, road and light conditions, posted speed limit, road type), vehicle and driver
149 characteristics, demographic details of the drivers, precrash manoeuvres of the vehicles, and the
150 initial impact point of the vehicle. Additionally, the dataset contains demographic information
151 and details regarding injury severity for each casualty. This study adhered to the STROBE
152 (strengthening the reporting of observational studies in epidemiology) reporting guidelines. (20)

153 The data that support the findings of this study are openly available at

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154 <https://figshare.com/ndownloader/files/48173452>.

155 Injury severity in the aforementioned dataset is divided into three categories, namely slight,
156 serious, and fatal. Fatal injuries refer to those leading to death within 30 days of the accident.
157 Serious injuries include conditions such as fractures, internal injuries, severe cuts and lacerations,
158 concussions, and any injury requiring hospitalisation. Slight injuries include sprains, bruises, and
159 minor cuts, as well as mild shock requiring roadside attention. The exclusive focus of this study
160 was crashes leading to cyclist casualties.

161 As shown in Figure 1, this study analysed 1,366,196 crashes involving bicycles and other
162 vehicles. Initially, 1,235,032 junction cases were excluded. From the remaining 131,164 bicycle
163 segment crashes, 3,527 were further excluded because of incomplete demographic data for the
164 cyclist and missing speed limit information, leaving a valid cohort of 127,637 bicycle segment
165 crashes for analysis. Within this cohort, this study identified 18,350 overtaking crashes, 44,962
166 rear-end crashes, 6,363 door crashes, and 57,962 other types of crashes.

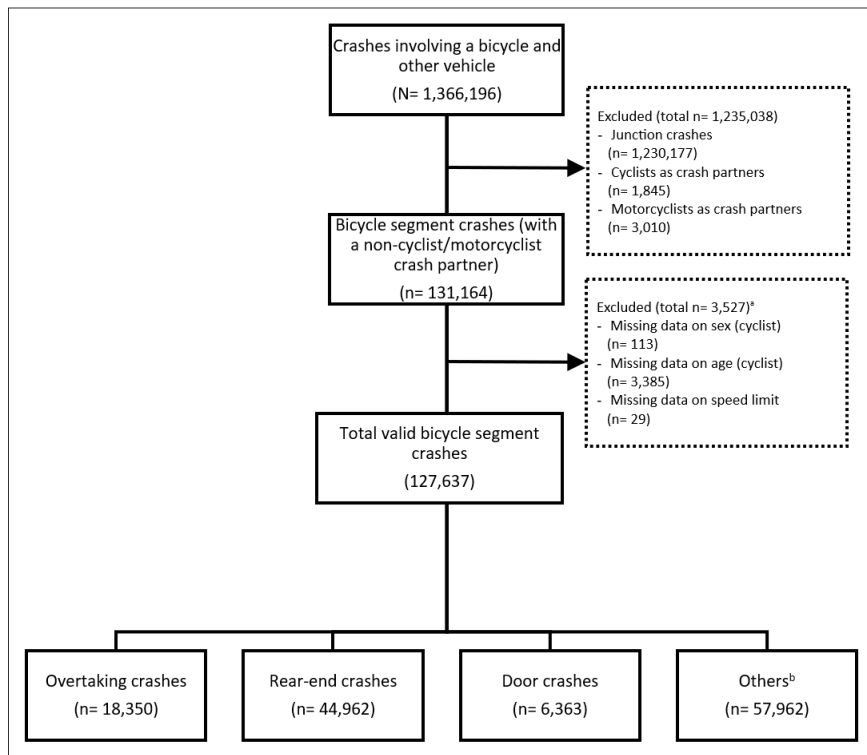


Figure 1. Flowchart of the study sample selection process.

^aListed excluded criteria are nonexclusive; thus, the sum of the total may exceed 3,527.

^bOther crashes include reversing crashes and head-on crashes.

Classification of crash types

As shown in Figure 2, an overtaking crash is defined as a crash where a motorised vehicle overtakes and impacts with a bicycle, which may be travelling straight, overtaking another vehicle, changing lanes, or turning. A rear-end crash occurs when a following vehicle impacts with the rear of a bicycle. A door crash involves a bicycle either being struck by or striking the opening door of an automobile. These three crash types were described using schematics in our previous study(18) .

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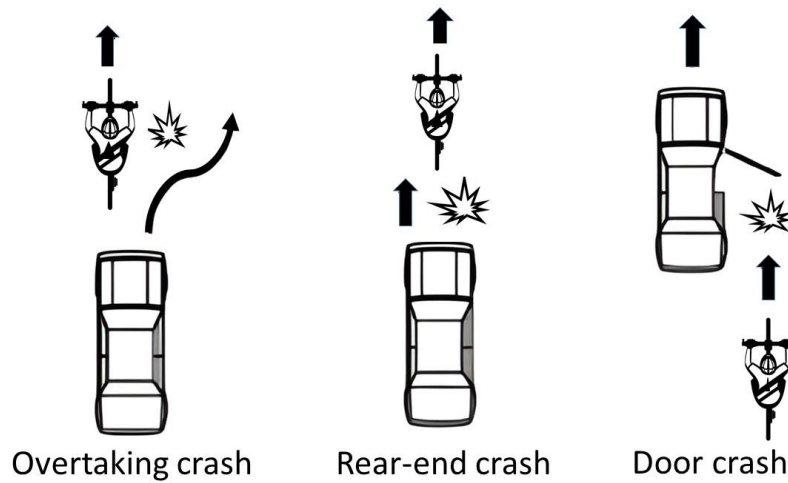


Figure 2. Illustrative diagram of the three crash types

Data analysis Data collection

For the present study, the three crash types of focus (overtaking, rear-end, and door crashes) were the binary-dependent variables. The collected data encompassed the following factors: lighting conditions on the roadway at the time of the crash (daylight, darkness-lit, darkness-unlit), the speed limit at the crash scene (rural: ≥ 40 miles per hour [mph]; urban: 20–30 mph), the time of day categorised into four periods according to traffic volume (midnight: 00:00–06:00; rush hours: 07:00–08:00 and 17:00–18:00; nonrush hours: 09:00–16:00; and evening: 19:00–23:00), and the day of the week (weekday or weekend day). The demographic details of cyclist casualties encompassed age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex (male or female). Finally, the demographic details of the crash partner included the type of vehicle (identified as a taxi, private hire car, car, bus, or heavy goods vehicle [HGV]), age (≤ 18 , 19–40, 41–64, or ≥ 65 years) and sex (male or female). On a cautionary note, we removed junction cases to avoid the variability

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193 introduced when exogenous factors, such as junction geometry and control measures, are
194 present at junctions. Furthermore, the cases involving other cyclists and motorcyclists were
195 removed as we focused on vehicle-cycle crashes only. Missing data on sex, age, or speed limits
196 were also excluded in the analysis. Excluding these data may impact our results in a marginal
197 scale, as these data are likely to be single-bicycle crashes that in nature be underreported in
198 police crash dataset (21).

199

200 **Statistical analysis**

201 This study employed the ~~chi~~Chi-squared test to examine the associations between crash type
202 and other factors, including cyclist or motorist characteristics, vehicle features, roadway
203 conditions, and temporal variables. We initially utilized descriptive statistics to examine the
204 distribution of crash types across various variables such as lighting conditions, speed limit, time
205 of day, and day of the week. Demographic details concerning cyclist casualties encompassed age
206 and sex, while information about the crash partner included vehicle type, age, and sex. This
207 preliminary analysis provided a general picture of basic characteristics of the data and
208 identification of potential patterns. For inferential analysis, we applied the Chi-squared test to
209 investigate associations between crash type and various factors, including cyclist and motorist
210 characteristics, vehicle features, roadway conditions, and temporal variables. We then estimated
211 crude odds ratios by estimating univariate logistic regression and adjusted odds ratios by
212 multivariate logistic models, respectively. ~~We initially utilized descriptive statistics to examine~~
213 ~~the distribution of crash types across various variables such as lighting conditions, speed limit,~~
214 ~~time of day, and day of the week.~~ Initially, we examined the distribution of three crash types

215 across various variables to explore their relationships with a binary outcome. These variables
216 included lighting conditions, speed limit, time of day, and day of the week. Demographic details
217 concerning cyclist casualties encompassed age and sex, while information about the crash
218 partner included vehicle type, age, and sex. This preliminary analysis helped us understand the
219 basic characteristics of the data and identify potential patterns. For inferential analysis, This
220 approach allowed us to identify significant predictors while controlling for potential confounding
221 variables. we applied the Chi-squared test to investigate associations between crash type and
222 various factors, including cyclist and motorist characteristics, vehicle features, roadway
223 conditions, and temporal variables. Specifically, we explored relationships between crash types
224 and binary outcomes related to variables such as lighting conditions and speed limits. We set a
225 significance level of $p < 0.2$ to include risk factors in our multivariate analysis [23]. Adjusted odds
226 ratios (AORs) were computed using multivariate logistic regression with backward selection. (22)

227 The multivariate logistic regression model equation was specified as:

$$\log\left(\frac{P(Y = 1)}{1 - P(Y = 1)}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

229 where $P(Y = 1)$ denotes the probability of the outcome, $\beta_0, \beta_1, \beta_2, \dots, \beta_p$ are the coefficients to be
230 estimated, and X_1, X_2, \dots, X_p represent the predictor variables.

231 Before estimating the model, assumptions of logistic regression, such as linearity of the logit,
232 absence of multicollinearity, and independence of observations, were evaluated. An odds ratio
233 (OR) greater than 1 indicated a positive association between the independent variable and the
234 occurrence rate, while an OR less than 1 indicated a negative association. An OR of 1 suggested

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235 no association between the variables of interest and the outcomes. Additionally, joint effect
 236 analysis was employed to assess the risk associated with the combination of variables across the
 237 three types of crashes. All statistical analyses were conducted using SPSS Statistics version 25 for
 238 Windows (IBM Corp., Armonk, New York, USA). A *p* value lower than 0.05 in two-tailed tests was
 239 considered statistically significant.

240

241 **Results**

242 **Population characteristics**

243 Tables 1, 2, and 3 present the distributions of overtaking, rear-end, and door crashes,
 244 respectively, in relation to multiple independent variables. These data revealed that a significant
 245 proportion of bicycle crashes occurred in daylight (82.3%), occurred in urban settings (78.5%),
 246 occurred during nonrush hours (48.3%), occurred on weekdays (77.5%), involved cyclists aged
 247 under 18 years (40.1%), and involved male cyclists (81.3%). Additionally, most crashes involved
 248 cars as crash partners (83.6%), and crash partners were predominately aged 19–40 years (38.5%)
 249 and were male (76.4%). Table 1 highlights an overrepresentation in bicycle overtaking crashes
 250 for certain variables, namely unlit darkness (19.5%), rural areas (24.8%), midnight hours (17.7%),
 251 buses or HGVs as crash partners (24.7%), and elderly crash partners (21.5%) and male crash
 252 partners (16.0%). These results were revealed to be statistically significant by the chi-squared
 253 test ($p < 0.01$).

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255 **Table 1.** Distribution of overtaking crashes according to a set of independent variables

Variable	Total (n=127,637)	Overtaking crashes (n=18,350)	Non-overtaking crashes (n=109,287)	χ^2 test <i>p</i> value
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Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	15,283 (14.655%)	89,770 (85.5%)	
Darkness-lit	16,543 (13.0%)	1,889 (11.429%)	14,654 (88.6%)	
Darkness-unlit	6,041 (4.7%)	1,178 (19.509%)	4,863 (80.5%)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5%)	6,805 (24.8%)	20,590 (75.6%)	
Urban (20–30 mph)	100,242 (78.5%)	11,545 (11.5%)	88,697 (88.5%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	852 (17.7%)	3,958 (82.3%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	5,685 (13.7%)	35,934 (86.3%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	9,386 (15.2%)	52,310 (84.8%)	
Evening (19:00–23:00)	19,512 (15.3%)	2,427 (12.4%)	17,085 (87.6%)	
Crash day, n (%)				0.094
Weekend	28,730 (22.5%)	4,218 (14.7%)	24,512 (85.2%)	
Weekday	98,907 (77.5%)	14,132 (14.3%)	84,775 (85.7%)	
Cyclist's age (years), n (%)				<0.001
≤18	51,193 (40.1%)	5,220 (10.2%)	45,973 (89.8%)	
19–40	45,760 (35.9%)	7,108 (15.5%)	38,652 (84.5%)	
41–64	26,052 (20.4%)	5,012 (19.2%)	21,040 (80.8%)	
≥65	4,632 (3.6%)	1,010 (21.8%)	3,622 (78.2%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	14,746 (14.2%)	89,020 (85.8%)	
Female	23,871 (18.7%)	3,604 (15.1%)	20,267 (84.9%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	208 (8.0%)	2,380 (92.0%)	
Car	106,668 (83.6%)	13,599 (12.8%)	93,069 (87.3%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	4,543 (24.7%)	13,838 (75.3%)	
Crash partner's age (years), n (%)				<0.001
≤18	2,415 (1.9%)	281 (11.6%)	2,134 (88.4%)	
19–40	49,103 (38.5%)	5,398 (11.0%)	43,705 (89.0%)	
41–64	35,598 (27.9%)	3,973 (11.2%)	31,625 (88.8%)	
≥65	40,521 (31.8%)	8,698 (21.5%)	31,823 (78.5%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.4%)	15,584 (16.0%)	81,863 (84.0%)	
Female	30,190 (23.8%)	2,766 (9.2%)	27,424 (90.8%)	

256

257

Several variables in Table 2 reveal significant differences between rear-end crashes and non-

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rear-end crashes. Specifically, a higher proportion of rear-end crashes occurred under darkness-

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unlit conditions (50.2%) compared to darkness-lit conditions (37.5%). Additionally, rear-end

260

crashes were more prevalent in rural areas with speed limits of ≥ 40 mph (43.0%) compared to

261

urban areas with speed limits of 20–30 mph (33.1%). Crashes involving crash partners aged ≥ 65

262 accounted for 39.7% of rear-end crashes, which was higher compared to other age groups (age
 263 41–64: 33.0% and ≤18: 36.0%). Furthermore, rear-end crashes were more likely to occur during
 264 midnight (47.6%) compared to rush hours (36.3%). Taxis [or private hire cars](#) were frequently
 265 involved in rear-end crashes (42.4%), as were male crash partners (36.8%). These findings
 266 highlight the significant influence of various factors on the likelihood of rear-end crashes.
 267 Variables such as darkness-unlit conditions, higher speed limits in rural areas, crash time, and
 268 characteristics of the crash partner all emerged as significant determinants. [Specifically, rear-end
 269 crashes were notably more prevalent under darkness-unlit conditions, in rural areas with higher
 270 speed limits, during midnight hours, and involving certain characteristics of crash partners.](#)
 271 Importantly, these associations were statistically significant, as indicated by the Chi-squared test
 272 ($p < 0.001$).

273
 274 **Table 2.** Distribution of rear-end crashes according to a set of independent variables

Variable	Total (n=127,637)	Rear-end crashes (n=44,962)	Non-rear-end crashes (n=82,675)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	35,726 (34.1%)	69,333 (66.0%)	
Darkness-lit	16,543 (13.0%)	6,204 (37.5%)	10,339 (63.5%)	
Darkness-unlit	6,041 (4.73%)	3,032 (50.19%)	3,003 (49.71%)	
Speed limit, n (%)				<0.001
Rural (≥ 40 mph)	27,395 (21.5%)	11,788 (43.0%)	15,607 (57.0%)	
Urban (20–30 mph)	100,242 (78.5%)	33,174 (33.1%)	67,068 (66.9%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	2,289 (47.6%)	2,521 (52.4%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	15,089 (36.3%)	26,530 (63.7%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	20,723 (33.6%)	40,973 (66.4%)	
Evening (19:00–23:00)	19,512 (15.3%)	6,861 (36.2%)	12,651 (64.9%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5%)	9,485 (33.0%)	19,245 (67.0%)	
Weekday	98,907 (77.5%)	35,477 (35.9%)	63,430 (64.1%)	
Cyclist's age (years), n (%)				<0.001
≤18	51,193 (40.1%)	13,446 (26.3%)	37,747 (73.7%)	
19–40	45,760 (35.9%)	19,102 (41.7%)	26,658 (58.3%)	
41–64	26,052 (20.4%)	10,619 (40.8%)	15,433 (59.2%)	
≥65	4,632 (3.6%)	1,795 (38.8%)	2,837 (61.3%)	

Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	37,175 (35.8%)	66,591 (64.2%)	
Female	23,871 (18.7%)	7,787 (32.6%)	16,084 (67.4%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	1,096 (42.4%)	1,492 (57.7%)	
Car	106,668 (83.6%)	37,202 (34.9%)	71,342 (66.9%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	6,664 (36.3%)	9,841 (53.5%)	
Crash partner's age (years), n (%)				<0.001
≤18	2,415 (1.9%)	870 (36.0%)	1,545 (64.0%)	
19–40	49,103 (38.5%)	16,282 (33.2%)	32,821 (66.8%)	
41–64	35,598 (27.9%)	11,736 (33.0%)	23,862 (67.0%)	
≥65	40,521 (31.8%)	16,074 (40.0%)	24,447 (60.3%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.6%)	35,828 (36.8%)	61,619 (63.2%)	
Female	30,190 (23.7%)	9,134 (30.3%)	21,056 (69.7%)	

275
276 As shown in Table 3, several variables can contribute to door crashes involving bicycles. Door
277 crashes predominantly occurred in urban areas with speed limits of 20-30 mph (6.2%), while a
278 significantly lower proportion occurred in rural areas with speed limits \geq 40 mph (0.5%). These
279 crashes were overrepresented during non-rush hours (5.5%) and rush hours (4.9%) compared to
280 evening (4.3%) and midnight (2.4%). Cyclists were more frequently involved in door crashes on
281 weekdays (5.4%) than weekends (3.7%). As many as 8.2% of all female cyclists were involved in
282 door crashes, which is higher than the involvement rate among males (4.2%). Taxi and private
283 hire cars were overinvolved in door crashes (10.6%) compared to cars (5.2%) and buses/heavy
284 goods vehicles (3.1%). Crash partners aged \leq 18 years (5.2%) and 19-40 years (5.3%) were
285 disproportionately involved in door crashes compared to older age groups, and female crash
286 partners were overrepresented in door crashes (7.4%) compared to males (4.2%). These results
287 were statistically significant, as indicated by the Chi-squared test ($p < 0.001$). They suggest that
288 various factors—including traffic conditions (rural areas, crash time), cyclist demographics
289 (younger age, [genderfemale](#)), and characteristics of the crash partner (taxi/private hire cars)—
290 significantly contribute to the likelihood of door crashes involving cyclists.

291 **Table 3.** Distribution of door crashes according to a set of independent variables

Variable	Total (n=127,637)	Door crashes (n=6,363)	Non-door crashes (n=121,274)	χ^2 test p value
Light conditions, n (%)				<0.001
Daylight	105,053 (82.3%)	5,192 (4.9%)	99,861 (95.1%)	
Darkness-lit	16,543 (13.0%)	1,031 (6.2%)	15,512 (93.8%)	
Darkness-unlit	6,041 (4.7%)	140 (2.3%)	5,901 (97.7%)	
Speed limit, n (%)				<0.001
Rural (\geq 40 mph)	27,395 (21.5%)	123 (0.5%)	27,272 (99.6%)	
Urban (20–30 mph)	100,242 (78.5%)	6,240 (6.2%)	94,002 (93.8%)	
Crash time (h), n (%)				<0.001
Midnight (00:00–06:00)	4,810 (3.8%)	113 (2.4%)	4,697 (97.7%)	
Rush hours (07:00–08:00/17:00–18:00)	41,619 (32.6%)	2,056 (4.9%)	39,563 (95.1%)	
Nonrush hours (09:00–16:00)	61,696 (48.3%)	3,363 (5.5%)	58,333 (94.6%)	
Evening (19:00–23:00)	19,512 (15.3%)	831 (4.3%)	18,681 (95.7%)	
Crash day, n (%)				<0.001
Weekend	28,730 (22.5%)	1,072 (3.7%)	27,658 (96.3%)	
Weekday	98,907 (77.5%)	5,291 (5.4%)	93,616 (94.7%)	
Cyclist's age (years), n (%)				<0.001
\leq 18	51,193 (40.1%)	802 (1.6%)	50,391 (98.4%)	
19–40	45,760 (35.9%)	3,474 (7.6%)	42,286 (93.4%)	
41–64	26,052 (20.4%)	1,773 (6.8%)	24,279 (93.2%)	
\geq 65	4,632 (3.6%)	314 (6.8%)	4,318 (93.2%)	
Cyclist's sex, n (%)				<0.001
Male	103,766 (81.3%)	4,404 (4.2%)	99,362 (95.8%)	
Female	23,871 (18.7%)	1,959 (8.2%)	21,912 (91.8%)	
Crash partner, n (%)				<0.001
Taxi/Private hire car	2,588 (2.0%)	273 (10.6%)	2,315 (89.5%)	
Car	106,668 (83.6%)	5,514 (5.2%)	101,154 (94.8%)	
Bus/Heavy goods vehicle	18,381 (14.4%)	576 (3.1%)	17,805 (96.9%)	
Crash partner's age (years), n (%)				<0.001
\leq 18	2,415 (1.9%)	1,62 (5.2%)	2,253 (93.3%)	
19–40	49,103 (38.5%)	2,585 (5.3%)	46,518 (94.7%)	
41–64	35,598 (27.9%)	1,887 (5.3%)	33,711 (94.7%)	
\geq 65	40,521 (31.8%)	1,729 (4.3%)	38,792 (95.7%)	
Crash partner's sex, n (%)				<0.001
Male	97,447 (76.6%)	4,123 (4.2%)	93,324 (95.8%)	
Female	30,190 (23.7%)	2,240 (7.4%)	27,950 (92.6%)	

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294 **Risk factors for the three crash types**

295

296 [Table 4 presents the results of the univariate logistic regression models. For overtaking crashes,](#)297 [lit conditions during darkness were associated with a lower likelihood of crashes compared to](#)298 [daylight \(AOR 0.80, 95% CI: 0.77–0.82, \$p < 0.001\$ \), while unlit conditions slightly increased the risk](#)299 [\(AOR 0.93, 95% CI: 0.99–0.95, \$p = 0.001\$ \). Urban roads with lower speed limits \(20–30 mph\)](#)

300 significantly reduced the odds of overtaking crashes compared to rural roads (AOR 0.40, 95% CI:
301 0.37–0.47, $p < 0.001$). In terms of cyclist demographics, older cyclists (≥ 65 years) were at a
302 notably higher risk (AOR 1.84, 95% CI: 1.78–1.97, $p < 0.001$), and male cyclists were more likely
303 to be involved than female cyclists (AOR 1.14, 95% CI: 1.10–1.17, $p < 0.001$). Additionally, crashes
304 involving buses or heavy goods vehicles increased the likelihood of overtaking crashes (AOR 1.31,
305 95% CI: 1.24–1.41, $p < 0.001$).
306 For rear-end crashes, both lit (AOR 1.11, 95% CI: 1.08–1.14, $p = 0.036$) and unlit (AOR 1.50, 95%
307 CI: 1.46–1.56, $p < 0.001$) darkness conditions were associated with a higher likelihood of
308 crashes compared to daylight. Urban roads were linked to a decreased risk of rear-end crashes
309 compared to rural roads (AOR 0.75, 95% CI: 0.73–0.79, $p < 0.001$). The likelihood of rear-end
310 crashes was significantly higher during midnight (AOR 1.34, 95% CI: 1.30–1.39, $p < 0.001$) and
311 rush hours (AOR 1.16, 95% CI: 1.12–1.20, $p = 0.003$). As with overtaking crashes, older cyclists
312 had an elevated risk (AOR 1.54, 95% CI: 1.51–1.80, $p < 0.001$), while males had slightly reduced
313 odds compared to females (AOR 0.81, 95% CI: 0.79–0.91, $p < 0.001$). Crashes involving buses or
314 heavy goods vehicles were slightly more likely to result in rear-end crashes (AOR 1.05, 95% CI:
315 1.01–1.15, $p < 0.001$). For door crashes, lit conditions during darkness were associated with
316 increased odds of crashes (AOR 1.19, 95% CI: 1.17–1.26, $p < 0.001$), whereas unlit conditions
317 did not show a significant difference compared to daylight (AOR 0.74, 95% CI: 0.72–1.02, $p =$
318 0.198). Urban environments with lower speed limits were strongly linked to a higher risk of
319 door crashes (AOR 15.3, 95% CI: 14.6–18.1, $p < 0.001$). Nonrush hours were also associated with
320 significantly higher odds (AOR 1.78, 95% CI: 1.68–1.89, $p < 0.001$). Older cyclists (≥ 65 years)
321 faced a substantially increased risk (AOR 5.13, 95% CI: 5.01–5.83, $p < 0.001$), and male cyclists

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322 were more likely to be involved than females (AOR 1.48, 95% CI: 1.33–1.67, $p < 0.001$).

323 Interestingly, crashes involving buses or heavy goods vehicles reduced the likelihood of door
324 crashes compared to cars (AOR 0.433, 95% CI: 0.40–0.51, $p < 0.001$).

325 Table 4 presents the logistic regression model results. Regarding overtaking crashes, the
326 identified risk factors included daylight conditions (adjusted odds ratio [AOR] = 1.233, 95%
327 confidence interval [CI] = 1.162–1.3091; $p < 0.001$), speed limits of ≥ 40 mph (AOR = 2.2438, 95%
328 CI = 2.1596–2.320; $p < 0.001$), nonrush hours (AOR = 1.091, 95% CI 1.031–1.154; $p = 0.003$), cyclists
329 aged ≥ 65 years (AOR = 1.7859, 95% CI = 1.6549–1.931; $p < 0.001$), female cyclists (AOR = 1.1106,
330 95% CI = 1.062–1.153), When HGVs are involved as crash partners, there is a 2.9 times greater
331 likelihood of being involved in an overtaking crash (AOR = 2.87, 95% CI = 2.47–3.32; $p <$
332 0.001). HGVs as crash partners (AOR = 2.867, 95% CI = 2.473–3.323; $p < 0.001$). Elderly crash
333 partners also demonstrated a doubled risk, with an AOR of 2.01 (95% CI = 1.94–2.09; $p <$
334 0.001). lderly crash partners (AOR = 2.013, 95% CI = 1.937–2.092; $p < 0.001$), and male crash
335 partners (AOR = 1.353, 95% CI = 1.292–1.4216; $p < 0.001$).

336 For rear-end crashes, noteworthy risk factors included unlit darkness (AOR = 1.4869, 95% CI
337 = 1.404–1.573; $p < 0.001$), speed limits of ≥ 40 mph (AOR = 1.3215, 95% CI = 1.2877–1.354;
338 $p < 0.001$), weekdays (AOR = 1.090, 95% CI = 1.0596–1.122; $p < 0.001$), midnight hours (AOR =
339 1.2769, 95% CI = 1.190–1.354; $p < 0.001$), and taxis as crash partners (AOR = 1.2869, 95% CI =
340 1.1869–1.394; $p < 0.001$).

341 Regarding door crashes, significant risk factors included lit darkness (AOR = 1.373, 95% CI =
342 1.141–1.651; $p < 0.001$), speed limits of 20–30 mph (AOR = 16.1859, 95% CI = 13.514–19.382;
343 $p < 0.001$), weekdays (AOR = 1.2465, 95% CI = 1.162–1.3364; $p < 0.001$), and nonrush hours (AOR =

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344 2.912, 95% CI = 2.384–3.556; $p < 0.001$). Additionally, female cyclists (AOR = 1.6875, 95% CI =
345 1.582–1.774; $p < 0.001$), taxis or private hire cars as crash partners (AOR = 2.70695, 95% CI =
346 2.310–3.145; $p < 0.001$), male crash partners (AOR = 1.373, 95% CI = 1.30296–1.4655; $p < 0.001$),
347 and crash partners aged 41–64 years (AOR = 1.8556, 95% CI = 1.6325–2.1217; $p < 0.001$) were
348 associated with door crashes.

349 Table 5 displays the results of the multivariate logistic regression analysis. For overtaking
350 crashes, for cyclists aged 65 years and older, the adjusted odds ratio (AOR) is 1.79 (95%
351 confidence interval [CI] = 1.65–1.93; $p < 0.001$), factors associated with a decreased likelihood of
352 crashes included daylight conditions (adjusted odds ratio [AOR] = 0.81, 95% confidence interval
353 [CI] = 0.80–0.84; $p < 0.001$), rural area with speed limits of 40 mph or higher (AOR = 0.45, 95% CI
354 = 0.43–0.47; $p < 0.001$). For cyclists aged 65 years and older, the adjusted odds ratio (AOR) is 1.79
355 (95% confidence interval [CI] = 1.65–1.93; $p < 0.001$). Furthermore, when heavy goods vehicles
356 (HGVs) are involved as crash partners, the likelihood of being involved in an overtaking crash
357 increase by 2.9 times (AOR = 2.87, 95% CI = 2.47–3.32; $p < 0.001$).

358 For rear-end crashes, significant risk factors included darkness or unlit conditions (AOR =
359 1.49, 95% confidence interval [CI] = 1.40–1.57; $p < 0.001$), crashes occurring on weekdays (AOR
360 = 1.09, 95% CI = 1.06–1.12; $p < 0.001$), and an increased likelihood of rear-end crashes during
361 rush hours (AOR = 1.12, 95% CI = 1.09–1.15; $p < 0.001$). In contrast, the risk was lower in urban
362 areas (AOR = 0.76, 95% CI = 0.74–0.79; $p < 0.001$), using rural areas as the reference.

363 For door crashes, notable risk factors included darkness or lit conditions (AOR = 1.23, 95%
364 confidence interval [CI] = 1.20–1.24; $p < 0.001$), a strong association with urban areas where
365 speed limits are between 20 and 30 mph (AOR = 16.2, 95% CI = 13.5–19.4; $p < 0.001$), and crashes

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366 [occurring on weekdays \(AOR = 1.25, 95% CI = 1.16–1.34; p < 0.001\)](#). Furthermore, female cyclists
 367 [exhibited higher odds of being involved in door crashes \(AOR = 1.68, 95% CI = 1.58–1.77; p <](#)
 368 [0.001\), and interactions with taxis or private hire cars as crash partners significantly increased](#)
 369 [the likelihood of door crashes \(AOR = 2.71, 95% CI = 2.31–3.15; p < 0.001\)](#). Furthermore, male
 370 [crash partners were associated with increased odds of door crashes \(AOR = 1.37, 95% CI = 1.30–](#)
 371 [1.47; p < 0.001\)](#), while crash partners aged 41–64 years also presented a heightened risk (AOR =
 372 [1.90, 95% CI = 1.81–1.93; p < 0.001\)](#).

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377 **Table 4.** Univariate logistic regression results

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Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Light condition						
Daylight	Ref		Ref		Ref	
Darkness-lit	0.80 (0.77, 0.82)	<0.001	1.11 (1.08, 1.14)	0.036	1.19 (1.17, 1.26)	<0.001
Darkness-unlit	0.93 (0.89, 0.95)	0.001	1.50 (1.46, 1.56)	<0.001	0.74 (0.72, 1.02)	0.198
Speed limit						
Rural (≥40 mph)	Ref		Ref		Ref	
Urban (20–30 mph)	0.40 (0.37, 0.47)	<0.001	0.75 (0.73, 0.79)	<0.001	15.3 (14.6, 18.1)	<0.001
Crash time						
Midnight	1.05 (0.97, 1.10)	0.157	1.34 (1.30, 1.39)	<0.001	0.39 (0.35, 0.47)	<0.001
Rush hours	1.04 (0.98, 1.08)	0.116	1.16 (1.12, 1.20)	0.003	1.36 (1.31, 1.55)	<0.001
Nonrush hours	1.12 (1.06, 1.14)	0.007	1.02 (0.97, 1.13)	0.742	1.78 (1.68, 1.89)	<0.001
Evening	Ref		Ref		Ref	
Crash day						
Weekend	Ref		Ref		Ref	
Weekday	0.92 (0.90, 1.04)	0.341	1.08 (1.07, 1.13)	<0.001	1.33 (1.25, 1.36)	<0.001
Cyclist's age (years)						
≤18	Ref		Ref		Ref	
19–40	1.28 (1.23, 1.39)	<0.001	1.80 (1.76, 1.99)	<0.001	5.26 (5.20, 5.86)	<0.001
41–64	1.47 (1.33, 1.61)	<0.001	1.68 (1.64, 1.81)	<0.001	5.66 (5.47, 6.00)	<0.001
≥65	1.84 (1.78, 1.97)	<0.001	1.54 (1.51, 1.80)	<0.001	5.13 (5.01, 5.83)	<0.001
Cyclist's sex						
Male	Ref		Ref		Ref	
Female	1.14 (1.10, 1.17)	<0.001	0.81 (0.79, 0.91)	<0.001	1.48 (1.33, 1.67)	<0.001
Crash partner						
Taxi/Private hire car	0.6328 (0.641, 0.680)	<0.001	1.274 (1.243, 1.334)	<0.001	1.78 (1.46, 1.82)	<0.001
Car			Ref		Ref	

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<u>Bus/Heavy goods vehicle</u>	Ref	<0.001	1.05 (1.01, 1.15)	<0.001	0.433 (0.40, 0.51)	<0.001
	1.31 (1.24, 1.41)					
<u>Crash partner's age (years)</u>						
≤18	1.03 (0.97, 1.21)	0.251	1.15 (1.11, 1.34)	<0.001	0.65 (0.62, 0.69)	<0.001
19–40	Ref		Ref		Ref	
41–64	0.93 (0.91, 0.98)	0.035	0.98 (0.97, 1.03)	0.138	0.96 (0.94, 0.99)	<0.001
≥65	2.33 (1.99, 2.56)	<0.001	1.25 (1.20, 1.31)	<0.001	0.51 (0.47, 0.56)	<0.001
<u>Crash partner's sex</u>						
Male	1.28 (1.25, 1.33)	<0.001	1.23 (1.15, 1.39)	<0.001	1.30 (1.25, 1.53)	<0.001
Female	Ref		Ref		Ref	

378 [Table 4 presents the results of the univariate logistic regression models. In terms of overtaking](#)
379 [crashes, conditions of darkness with lighting \(AOR 0.80, 95% CI: 0.77–0.82, p < 0.001\) and](#)
380 [darkness without lighting \(AOR 0.93, 95% CI: 0.89–0.95, p = 0.001\) were linked to a reduced](#)
381 [likelihood of crashes when compared to daylight conditions. Urban roads with lower speed limits](#)
382 [\(20–30 mph\) significantly reduced the odds of overtaking crashes compared to rural roads \(AOR](#)
383 [0.40, 95% CI: 0.37–0.47, p < 0.001\). In terms of cyclist demographics, older cyclists \(≥65 years\)](#)
384 [were at a notably higher risk \(AOR 1.84, 95% CI: 1.78–1.97, p < 0.001\), and male cyclists were](#)
385 [more likely to be involved than female cyclists \(AOR 1.14, 95% CI: 1.10–1.17, p < 0.001\).](#)
386 [Additionally, crashes involving buses or heavy goods vehicles \(HGVs\) increased the likelihood of](#)
387 [overtaking crashes \(AOR 1.31, 95% CI: 1.24–1.41, p < 0.001\).](#)

388 [For rear-end crashes, both lit \(AOR 1.11, 95% CI: 1.08–1.14, p = 0.036\) and unlit \(AOR 1.50,](#)
389 [95% CI: 1.46–1.56, p < 0.001\) darkness conditions were associated with a higher likelihood of](#)
390 [crashes compared to daylight. Urban areas were linked to a decreased risk of rear-end crashes](#)
391 [compared to rural areas \(AOR 0.75, 95% CI: 0.73–0.79, p < 0.001\). The likelihood of rear-end](#)
392 [crashes was significantly higher during midnight \(AOR 1.34, 95% CI: 1.30–1.39, p < 0.001\) and](#)
393 [rush hours \(AOR 1.16, 95% CI: 1.12–1.20, p = 0.003\). As with overtaking crashes, older cyclists](#)
394 [had an elevated risk \(AOR 1.54, 95% CI: 1.51–1.80, p < 0.001\), while males had slightly reduced](#)
395 [odds compared to females \(AOR 0.81, 95% CI: 0.79–0.91, p < 0.001\). Crashes involving buses or](#)

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396 [heavy goods vehicles were slightly more likely to result in rear-end crashes \(AOR 1.05, 95% CI:](#)
 397 [1.01–1.15, p < 0.001\).](#)

398 [Regarding door crashes, lit conditions during darkness were associated with increased odds of](#)
 399 [crashes \(AOR 1.19, 95% CI: 1.17–1.26, p < 0.001\), whereas unlit conditions did not show a](#)
 400 [significant difference compared to daylight \(AOR 0.74, 95% CI: 0.72–1.02, p = 0.198\). Urban](#)
 401 [environments with lower speed limits were strongly linked to a higher risk of door crashes \(AOR](#)
 402 [15.3, 95% CI: 14.6–18.1, p < 0.001\). Older cyclists \(≥65 years\) faced a substantially increased risk](#)
 403 [\(AOR 5.13, 95% CI: 5.01–5.83, p < 0.001\), and male cyclists were more likely to be involved than](#)
 404 [females \(AOR 1.48, 95% CI: 1.33–1.67, p < 0.001\). Interestingly, crashes involving buses or heavy](#)
 405 [goods vehicles reduced the likelihood of door crashes compared to cars \(AOR 0.433, 95% CI:](#)
 406 [0.40–0.51, p < 0.001\).](#)

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410 **Table 45.** Multivariate logistic regression results

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Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p-value	AOR (95% CI)	p-value	AOR (95% CI)	p-value
Light condition						
Daylight	1.233 (1.162, 1.30931)	<0.001	Ref		1.14615 (0.95896, 1.370)	0.137
Darkness-lit	Ref		1.08509	0.041	1.373 (1.141, 1.651)	0.001
Darkness-unlit	1.152 (1.05906, 1.253)	0.001	1.48649 (1.404, 1.573)	<0.001	Ref	
Speed limit						
Rural (≥40 mph)	2.23824 (2.15916, 2.320)	<0.001	1.31532 (1.27728, 1.354)	<0.001	Ref	
Urban (20–30 mph)	Ref		Ref		16.18519 (12.514, 19.382)	<0.001
Crash time						
Midnight	1.073 (0.982, 1.173)	0.119	1.26927 (1.190, 1.354)	<0.001	Ref	
Rush hours	1.05906 (1.002, 1.120)	0.043	1.10811 (1.078, 1.1394)	<0.001	2.502 (2.051, 3.052)	<0.001
Nonrush hours	1.091 (1.031, 1.154)	0.003	Ref		2.912 (2.384, 3.556)	<0.001
Evening	Ref		0.992 (0.953, 1.032)	0.686	2.014 (1.64665, 2.46547)	<0.001

Table 4. Multivariate logistic regression results (continued)

Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Crash day						
Weekend	1.031 (0.991, 1.072)	0.132	Ref		Ref	
Weekday	Ref		1.090 (1.0659, 1.122)	<0.001	1.246 <u>25</u> (1.162, 1.33634)	<0.001
Cyclist's age (years)						
≤18	1.292 (1.242, 1.345)		Ref		Ref	
19-40	1.509 <u>51</u> (1.444, 1.578)	<0.001	1.839 <u>84</u> (1.7889, 1.891)	<0.001	5.943 (5.489, 6.43544)	<0.001
41-64	1.785 <u>70</u> (1.64965, 1.931)	<0.001	1.731 (1.6768, 1.789)	<0.001	6.129 <u>13</u> (5.621, 6.684)	<0.001
≥65			1.671 (1.5687, 1.780)	<0.001	5.9889 (5.21722, 6.874)	<0.001
Cyclist's sex						
Male	Ref		1.172 (1.13714, 1.2081)	<0.001	Ref	
Female	1.106 <u>11</u> (1.062, 1.153)	<0.001	Ref		1.675 <u>68</u> (1.582, 1.774)	<0.001
Crash partner						
Taxi/Private hire car	Ref		1.286 <u>29</u> (1.1869, 1.394)	<0.001	2.695 <u>70</u> (2.310, 3.145)	<0.001
Car	1.571 (1.35936, 1.81682)	<0.001	Ref		2.089 (1.9081, 2.28629)	<0.001
Bus/Heavy goods vehicle	2.867 (2.473, 3.323)	<0.001	1.099 <u>10</u> (1.061, 1.13914)	<0.001	Ref	
Crash partner's age (years)						
≤18	1.1097 (0.963, 1.24925)	0.162	1.225 <u>23</u> (1.18819, 1.263)	<0.001	1.507 <u>51</u> (1.313311, 1.731731)	<0.001
19-40	Ref		1.038 <u>04</u> (1.00801, 1.06997)	0.013	1.855 <u>86</u> (1.62563, 2.11712)	<0.001
41-64	0.950 (0.90991, 0.994)	0.025	Ref		Ref	
≥65	2.013 (1.93794, 2.092)	<0.001	1.241 (1.13714, 1.35536)	<0.001	1.801 (1.574, 2.060)	<0.001
Crash partner's sex						
Male	1.353 (1.292, 1.4162)	<0.001	1.150 (1.11712, 1.18519)	<0.001	1.373 (1.29630, 1.45546)	<0.001
Female	Ref		Ref		Ref	

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Variable	Overtaking crashes		Rear-end crashes		Door crashes	
	AOR (95% CI)	p value	AOR (95% CI)	p value	AOR (95% CI)	p value
Light condition						
Daylight	Ref		Ref		Ref	
Darkness-lit	0.81 (0.80, 0.84)	<0.001	1.04 (1.00, 1.09)	0.041	1.23 (1.20, 1.24)	<0.001
Darkness-unlit	0.92 (0.90, 0.93)	0.001	1.49 (1.40, 1.57)	<0.001	0.87 (0.86, 1.02)	0.136
Speed limit						
Rural (≥40 mph)	Ref		Ref		Ref	
Urban (20-30 mph)	0.45 (0.43, 0.47)	<0.001	0.76 (0.74, 0.79)	<0.001	16.2 (13.5, 19.4)	<0.001
Crash time						
Midnight	1.07 (0.98, 1.17)	0.119	1.28 (1.21, 1.40)	<0.001	0.50 (0.46, 0.53)	<0.001

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Rush hours	<u>1.06 (1.00, 1.12)</u>	<u>0.043</u>	<u>1.12 (1.09, 1.15)</u>	<u><0.001</u>	<u>1.49 (1.45, 1.62)</u>	<u><0.001</u>
Nonrush hours	<u>1.09 (1.03, 1.15)</u>	<u>0.003</u>	<u>1.01 (0.96, 1.10)</u>	<u>0.639</u>	<u>1.90 (1.81, 1.93)</u>	<u><0.001</u>
Evening	Ref		Ref		Ref	
Crash day						
Weekend	Ref		Ref		Ref	
Weekday	<u>0.97 (0.96, 1.01)</u>	<u>0.133</u>	<u>1.09 (1.06, 1.12)</u>	<u><0.001</u>	<u>1.25 (1.16, 1.34)</u>	<u><0.001</u>
Cyclist's age (years)						
≤18	Ref		Ref		Ref	
19–40	<u>1.29 (1.24, 1.35)</u>	<u><0.001</u>	<u>1.84 (1.79, 1.89)</u>	<u><0.001</u>	<u>5.94 (5.49, 6.44)</u>	<u><0.001</u>
41–64	<u>1.51 (1.44, 1.58)</u>	<u><0.001</u>	<u>1.73 (1.68, 1.79)</u>	<u><0.001</u>	<u>6.13 (5.62, 6.68)</u>	<u><0.001</u>
≥65	<u>1.79 (1.65, 1.93)</u>	<u><0.001</u>	<u>1.67 (1.57, 1.78)</u>	<u><0.001</u>	<u>5.99 (5.22, 6.87)</u>	<u><0.001</u>
Cyclist's sex						
Male	Ref		Ref		Ref	
Female	<u>1.11 (1.06, 1.15)</u>	<u><0.001</u>	<u>0.85 (0.83, 0.90)</u>	<u><0.001</u>	<u>1.68 (1.58, 1.77)</u>	<u><0.001</u>
Crash partner						
Taxi/Private hire car						
Car	<u>0.64 (0.61, 0.69)</u>	<u><0.001</u>	<u>1.29 (1.19, 1.39)</u>	<u><0.001</u>	<u>1.61 (1.59, 1.69)</u>	<u><0.001</u>
Bus/Heavy goods vehicle/HGV	Ref		Ref		Ref	
Car	<u>1.30 (1.27, 1.33)</u>	<u><0.001</u>	<u>1.10 (1.06, 1.14)</u>	<u><0.001</u>	<u>0.48 (0.45, 0.49)</u>	<u><0.001</u>
Crash partner's age (years)						
≤18	<u>1.10 (0.96, 1.25)</u>	<u>0.162</u>	<u>1.19 (1.17, 1.24)</u>	<u><0.001</u>	<u>0.65 (0.63, 0.68)</u>	<u><0.001</u>
19–40	Ref		Ref		Ref	
41–64	<u>0.95 (0.91, 0.99)</u>	<u>0.025</u>	<u>0.96 (0.95, 0.98)</u>	<u>0.026</u>	<u>0.95 (0.93, 0.98)</u>	<u><0.001</u>
≥65	<u>2.01 (1.94, 2.09)</u>	<u><0.001</u>	<u>1.20 (1.18, 1.31)</u>	<u><0.001</u>	<u>0.54 (0.52, 0.57)</u>	<u><0.001</u>
Crash partner's sex						
Male	<u>1.35 (1.29, 1.42)</u>	<u><0.001</u>	<u>1.15 (1.12, 1.19)</u>	<u><0.001</u>	<u>1.37 (1.30, 1.46)</u>	<u><0.001</u>
Female	Ref		Ref		Ref	

413 [Table 5 presents the results of the multivariate logistic regression analysis. In overtaking](#)
414 [crashes, the presence of HGVs as partners increases the likelihood by 1.3 times \(AOR = 1.30, 95%](#)
415 [CI = 1.27–1.33; p < 0.001\). For cyclists aged 65 and older, the adjusted odds ratio \(AOR\) is 1.79](#)
416 [\(95% CI = 1.65–1.93; p < 0.001\) compared to those aged 18 and younger. Factors associated with](#)
417 [a decreased likelihood of crashes include daylight conditions \(AOR = 0.81, 95% CI = 0.80–0.84; p](#)
418 [< 0.001\) and rural areas with speed limits of 40 mph or higher \(AOR = 0.45, 95% CI = 0.43–0.47;](#)
419 [p < 0.001\).](#)

420 [For rear-end crashes, significant risk factors included darkness and unlit conditions \(AOR =](#)
421 [1.49, 95% confidence interval \[CI\] = 1.40–1.57; p < 0.001\), crashes occurring on weekdays \(AOR](#)
422 [= 1.09, 95% CI = 1.06–1.12; p < 0.001\), and an increased likelihood of rear-end crashes during](#)

423 [rush hours \(AOR = 1.12, 95% CI = 1.09–1.15; p < 0.001\)](#). In contrast, the risk is lower in urban
424 [areas \(AOR = 0.76, 95% CI = 0.74–0.79; p < 0.001\)](#) when rural areas are used as the reference.

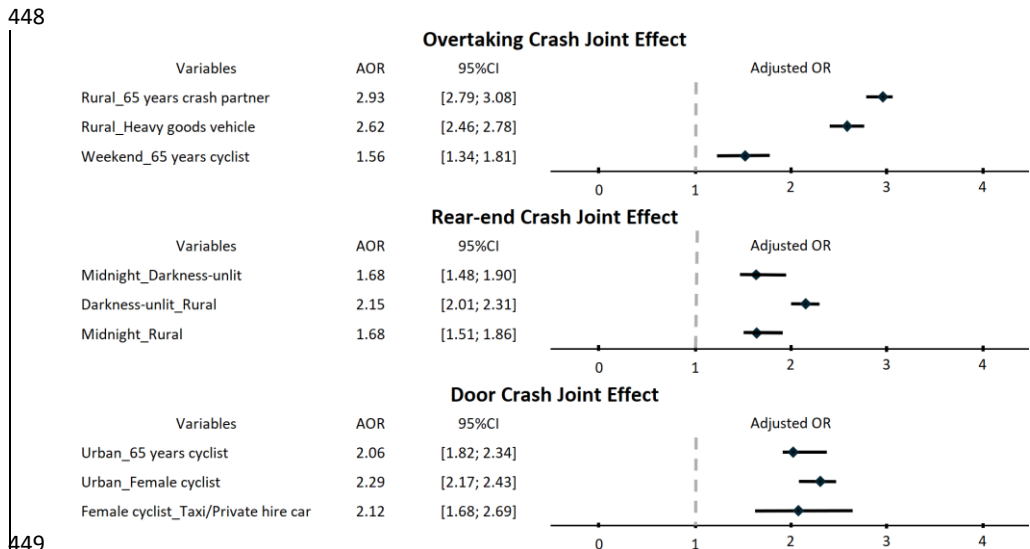
425 [Door crashes are significantly more prevalent in urban areas with speed limits of 20 to 30](#)
426 [mph—approximately 16 times higher \(AOR = 16.2, 95% CI = 13.5–19.4; p < 0.001\)](#). Additionally,
427 [interactions with taxis or private hire cars as crash partners further increase the likelihood of](#)
428 [these crashes \(AOR = 1.61, 95% CI = 1.59–1.69; p < 0.001\)](#). Other important risk factors include
429 [conditions of darkness with illumination \(AOR = 1.23, 95% CI = 1.20–1.24; p < 0.001\)](#) and crashes
430 [occurring on weekdays \(AOR = 1.25, 95% CI = 1.16–1.34; p < 0.001\)](#). Furthermore, male crash
431 [partners were associated with increased odds of door crashes \(AOR = 1.37, 95% CI = 1.30–1.47;](#)
432 [p < 0.001\)](#).

433 ▲
434 Figure 2 presents a forest plot demonstrating the joint effects of several variables on the
435 three crash types when other variables were controlled for. The results identified several key risk
436 factors for both overtaking and rear-end crashes. The risk of overtaking crashes showed a
437 significant increase of 193% in rural areas when elderly drivers were involved (AOR = 2.93, 95%
438 CI = 2.79–3.08), and similarly when heavy goods vehicles (HGVs) were the crash partner (AOR =
439 2.62, 95% CI = 2.46–2.78). Elderly cyclists also faced a higher risk of overtaking crashes on
440 weekends (AOR = 1.56, 95% CI = 1.34–1.81).

441 Regarding rear-end crashes, the risk increased notably with unlit darkness during
442 midnight (AOR = 1.68, 95% CI = 1.48–1.90) and was significantly higher in rural areas (AOR = 2.15,
443 95% CI = 2.01–2.31). Furthermore, bicycling at midnight in rural areas was associated with an
444 increased risk of rear-end crashes (AOR = 1.68; 95% CI = 1.51–1.86). In urban settings, the risk of
445 door crashes was higher for female cyclists (AOR = 2.29; 95% CI = 2.17–2.43) and for elderly

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446 cyclists (AOR = 2.06; 95% CI = 1.82–2.34). Finally, female cyclists exhibited a 112% higher
 447 likelihood of door crashes when the crash partner was a taxi (AOR = 2.12; 95% CI = 1.68–2.69).



449 **Figure 3.** Joint effects of several variables on the three crash types.
 450
 451
 452
 453
 454

455 **Discussion**

456 This study explored the relationships among individual and environmental factors in relation
 457 to three common bicycle crash types (overtaking, rear-end, and door crashes) on roads in the
 458 United Kingdom from 1991 to 2020. The findings revealed several significant factors. First, for
 459 overtaking crashes, HGVs as crash partners, rural areas, and the involvement of elderly crash
 460 partners emerged as key contributing factors. Second, unlit darkness, midnight hours, and rural
 461 areas were the factors most closely associated with rear-end crashes. Third, urban areas and taxis
 462 as crash partners significantly increased the likelihood of door crashes. Moreover, male crash

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463 partners were found to be a consistent risk factor across all three crash types.

464 Our research findings identified specific risk factors for overtaking crashes, namely rural
465 areas, HGVs as crash partners, and elderly crash partners. These findings align with previous
466 research that identified elderly drivers (23), speeds exceeding 10 mph, and the presence of pick-
467 up trucks as factors contributing to increased risk for overtaking crash. Specifically, HGVs possess
468 several characteristics that amplify this danger. Their large blind spots make it difficult for drivers
469 to see cyclists, increasing the likelihood of crashes during overtaking (24) [\[1\]](#). Additionally, HGVs
470 are less manoeuvrable compared to passenger cars, which reduces their ability to avoid crashes
471 if cyclists suddenly enter their path (25) [\[1\]](#). The speed and distance perception issues between
472 HGVs and cyclists further complicate the judgment of safe overtaking gaps (26) [\[1\]](#). Furthermore,
473 HGVs require longer stopping distances due to their size and weight, which can lead to severe
474 consequences if a sudden need to brake arises. A behavioural study suggested that compared
475 with cars, HGVs tended to maintain a narrower clearance zone when overtaking bicycles (27).
476 Regarding the association with buses or HGVs, Pai et al. suggested that time pressures on HGV
477 drivers for timely loading and unloading might lead to more reckless driving (18). Specifically, our
478 results align with the observations made by Pai et al., who also mentioned higher crash rates
479 involving buses or HGVs, supporting the idea that these time pressures contribute to increased
480 crash risks. Our findings underscore the necessity of implementing measures such as 'Share the
481 Road' warning signs (28), particularly in rural settings, where HGVs are likely to execute
482 overtaking manoeuvres at high speed. Such measures could prompt motor vehicles to maintain
483 safer distances from the edges of travel lanes, especially in areas with a notable presence of both
484 HGVs and bicycles.

485 We also identified elderly drivers as a factor contributing to overtaking crashes—a finding
486 consistent with relevant research (23). We found that as individuals age, their risk of being
487 involved in road accidents increases, primarily due to declines in cognitive capabilities. Our study
488 corroborates these findings by showing that older cyclists are more susceptible to accidents
489 during overtaking manoeuvres, which can be attributed to diminished reaction times and
490 impaired decision-making abilities (29), their health (30), and their driving performance (31).
491 Notably, crashes involving elderly individuals often occur in scenarios with challenging conditions,
492 including at intersections without traffic control measures, on high-speed roads, during adverse
493 weather conditions, in poorly lit areas, and in head-on accidents (32-34). The heightened level of
494 risk under such conditions may be attributed to cognitive and perceptual decline in older drivers,
495 which could affect their capacity to execute actions such as overtaking manoeuvres safely.
496 Accordingly, developing specialised cognitive training programmes as interventions to enhance
497 road safety for elderly drivers is evidently necessary (35). Based on our study's findings, we
498 recommend the development of specialised interventions to improve road safety for elderly
499 cyclists. Our analysis reveals that older cyclists are at a higher risk of being involved in overtaking
500 crashes, with this increased risk being strongly linked to declines in cognitive capabilities
501 associated with aging. To address this issue, we advocate for the implementation of targeted
502 cognitive training programs specifically designed for elderly cyclists. These programs should focus
503 on enhancing critical skills such as reaction time, situational awareness, and decision-making
504 abilities, which are crucial for reducing crash risk and improving overall road safety.

505 In the present study, several factors were found to increase the risk of rear-end crashes on
506 road segments, including darkness with unlit surroundings, midnight hours, and rural settings

507 (speed limit > 40 mph). Although few studies have specifically addressed rear-end crashes
508 involving bicycles on road segments, available data suggest that the low conspicuity of bicycles,
509 especially at night, is a recurrent factor in rear-end crashes(18) . Moreover, a lack of adequate
510 street lighting, which is common in rural settings, predisposes cyclists to rear-end crashes-. Our
511 joint-effects analysis further indicated that the detrimental effect of unlit darkness is more
512 pronounced in rural areas and during midnight hours. Potential intervention strategies to
513 mitigate rear-end crashes include enhancing illumination and executing speed control
514 management on rural road segments with heavy bicycle traffic.

515 Next, our analysis successfully identified associations of urban areas and taxis and private
516 hire cars as crash partners with door crashes on road segments. Although research specifically
517 focusing on door crashes on road segments is limited, similar findings were documented by Pai,
518 indicating that urban roadways and taxis contributed to door crashes (18). However, determining
519 the factors influencing this trend poses a challenge. One possible explanation could be the
520 increased presence of taxis or private hire cars in such areas, where passengers often disembark.
521 Additionally, our analysis further revealed an elevated risk of door crashes involving crashes with
522 taxis in urban areas. To reduce door crashes on road segments, educating taxi drivers, as well as
523 passengers, about the importance of vigilance when opening doors near traffic is essential (18).
524 In addition, cyclists should be advised to maintain at least a door's width distance from all parked
525 cars to improve the sight triangles of drivers and increase the visibility of cyclists (36).
526 Implementing a two-stage door opening mechanism for vehicles, which would enable drivers to
527 verify the presence of bicycles to the rear, could also be beneficial (37).

528 The strengths of this study include the use of STATS19 datasets spanning from 1991 to 2020,

529 which provides a robust statistical foundation and a broad perspective on trends in bicycle
530 crashes. By focusing specifically on three crash types on road segments—overtaking, rear-end,
531 and door crashes—the study provides a comprehensive and focused analysis, which can yield
532 more actionable insights and more effective recommendations. The UK-based dataset ensures
533 that the findings are particularly relevant for local policy and safety interventions. Additionally,
534 the application of statistical techniques and the consideration of various factors, such as crash
535 partner and time of day, enhance the validity and depth of the analysis.

536 This study had several limitations that warrant acknowledgement. First, the substantial
537 underreporting of nonfatal casualties to the police, particularly casualties involving cyclists not
538 obligated to report accidents, is a critical factor to consider. Such underreporting, as highlighted
539 by the U.K. Government’s Department for Transport (11), likely results in the incomplete
540 representation of nonfatal and ‘slight’ casualties in road casualty data. Second, the STATS19 data
541 utilised in this study lack critical variables, including precrash speeds, specific geometric
542 characteristics of roadways, data regarding alcohol and illicit substance use, and cyclist speed at
543 the time of an accident. Moreover, critical exposure data—such as those related to traffic flow,
544 rider or driver experience, and other elements of risk exposure—are absent, and the absence of
545 such details limits our ability to fully account for potential variations resulting from unobserved
546 factors in the analyses. Finally, this study did not explore annual trends in each type of bicycle
547 crash over the 30-year study period; investigating such trends could provide insights regarding
548 changing behaviours among cyclists and motor vehicle drivers as well as the effects of legislative
549 changes for road speed limits.

550 One inherent problem with police-reported crash data is the variables not readily available,

551 hereby causing unobserved heterogeneity across the observations. To overcome such a
552 limitation, we estimated separate regression models, as suggested by Kim et al.(38), for the three
553 crash types; such an approach provides greater explanatory power compared to single overall
554 models. Further, we conducted joint-effect analyses of several variables of interest that capture
555 heterogeneity. In our previous studies, we adopted the above-mentioned approaches to
556 overcome the inherent problem with a success (39, 40).

557 Future research directions could involve integrating GPS (Global Positioning System) data
558 and weather conditions to analyse both injury frequency and fatalities of bicycle crashes on road
559 segments. Additionally, exploring the potential of autonomous vehicles for detecting
560 approaching bicycles for door-crashes and implementing AI-controlled lighting systems in rural
561 areas for cyclist detection could be promising areas for further study.

562

563 **Recommendations**

564 For overtaking crashes, we recommend implementing 'Share the Road' warning signs,
565 especially in rural areas, and developing specialized cognitive training programs for elderly
566 drivers. Regarding rear-end crashes, our suggestions include improving illumination during night
567 time and implementing speed control measures on rural road segments. For door crashes
568 involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility.
569 Moreover, implementing a two-stage door opening mechanism and an automatic detection
570 device in vehicles to alert drivers of bicycles approaching from behind could potentially be
571 beneficial.

572

573 **Conclusions**

574 This study identified several significant risk factors for the three predominate types of crashes
575 involving cyclists on road segments: HGVs as crash partners, elderly crash partners, and rural
576 areas for overtaking crashes; unlit darkness, midnight hours, and rural areas for rear-end crashes;
577 and urban areas and taxis as crash partners for door crashes. These risk factors remained
578 unchanged since our previous study conducted in 2011 ~~(15)~~(18). The present research enhances
579 the field of bicycle safety research by concluding that the detrimental effects of certain variables
580 become more pronounced under certain conditions. For example, first, cyclists in rural settings
581 exhibited an elevated risk of overtaking crashes involving HGVs. Second, the rear-end crash risk
582 increases in the combined presence of unlit darkness, midnight hours, and rural areas. Finally, in
583 urban settings, the likelihood of door crashes increases when a taxi is the crash partner.

584

585 **Abbreviations**

586 WHO: World Health Organization; HGVs: heavy goods vehicles; AOR: adjusted odds ratio; CI:
587 confidence interval.

588

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591

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602

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609 ~~interpretation of data, or preparation of the manuscript.~~

610

611 **Availability of data and materials**

612 This study utilised the British STATS19 database, which contains data on all road traffic accidents

613 in the United Kingdom. The data that support the findings of this study are openly available at

614 <https://figshare.com/ndownloader/files/48173452>.

615

616 **Declarations**

617 **Ethical approval and consent to participate**

618 This study was conducted in accordance with the Declaration of Helsinki and approved by the
619 Joint Institutional Review Board of Taipei Medical University (N202011030).

620

621 **Consent for publication**

622 This study was approved by the Joint Institutional Review Board of Taipei Medical
623 University (N202011030). The Joint Institutional Review Board of Taipei Medical University has
624 waived the requirement of informed consent. All methods were performed in accordance with
625 the relevant guidelines and regulations of the Declaration of Helsinki.

626

627 **Competing interests**

628 The authors declare that they have no competing interests in relation to this work.

629

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756 [_____](#)

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Dear Editors and Reviewers,

We greatly appreciate the valuable comments and suggestions raised by reviewers. Please very kindly see our responses below, as well as the revised manuscript. We would be glad if you could have our manuscript reviewed again.

Best regards,

Chih-Wei Pai (Prof)

Graduate Institute of Injury Prevention and Control College of Public Health

Taipei Medical University

Reviewer comments:

Reviewer 1: Regarding the statistical analysis, I would like to ask the authors to explain:
1. the reason(s) for ignoring any probable interaction between independent variables in the multivariate logistic regression.

Author's response: We appreciate the reviewer's comment and question. By examining variables independently, we gain a clearer understanding of their individual impacts on the outcome (specifically, crash type in this study). This approach allows us to assess each variable's direct influence without the added complexity of interactions or modifications between variables. It provides insights into which variables independently affect the outcome, directly addressing our research questions. Initially, we used the chi-squared test to explore associations between a set of independent variables and the three crash types. To minimize type II errors in variable selection and ensure unbiased inferences, we included variables with a p-value less than 0.2 from the univariate analysis into the multivariate logistic regression models, a common practice in past studies of traffic injuries (e.g., a, b) and methodology (c). Subsequently, we examined interaction effects among several variables of interest, as depicted in Figure 2 of the manuscript. While acknowledging the potential for other interactions among variables, our study focused on assessing the joint effects of specific variables of interest. To take overtaking crashes as an example, these variables included rural areas, crash partners aged 65 years or older, heavy goods vehicles, weekends, and cyclists aged 65 years or older. Future research could delve into untangling the complexities of additional interaction effects among variables, as suggested by the reviewer.

References:

a: Chen, P-L, Pai, C-W. Evaluation of injuries sustained by motorcyclists in approach-turn crashes in Taiwan. *Accident Analysis and Prevention*, 2019, 124, 33-39.

b: Chien, D-K., Hwang, HF, Lin, MR. Injury severity measures for predicting return-to-work after a traumatic brain injury. *Accident Analysis and Prevention*, 2017, 98, 101-107.

c: Maldonado G, Greenland S. Simulation study of confounder-selection strategies. *Am J Epidemiol* 1993, 138, 11, 923-936.

2. Why did they consider different reference categories for the same individual variables among different outcomes in logistic regression modeling? This will make it difficult to interpret the comparison of the effect of an independent variable on different types of crashes. for example, in table 4, the ref category for Light condition is

Darkness-lit, Daylight and Darkness-unlit for Overtaking, Rear-end and Door crashes respectively.

Author's response: We appreciate the reviewer's comment and question. In our analysis, we chose various reference categories for variables based on the lowest Adjusted Odds Ratios (AORs) observed. This approach allowed us to highlight different risk factors associated with higher AORs for specific types of crashes. For example, urban roads with speed limits of 20-30 mph were identified as protective factors for overtaking and rear-end crashes. However, for door crashes, these urban roads appeared to pose a higher risk compared to rural roads, as indicated by their higher AOR. It is important to note that selecting a reference category does not change the estimation results of our models. Instead, assigning reference case with the lowest AOR helps readers identify risk factors with higher AORs among the three crash types.

3. I suggest authors provide identical indicators for figures both in the main text and in the figure's caption. Reading "Fig. 1" below a figure, one will look for the same word in the main text while it is recalled as "Figure 1".

Author's response: We appreciate this reviewer's comments, and we have revised the manuscript in the main text and figure's caption (please refer to lines 145 to 146; page 8 in the manuscript).

Reviewer 2:

1 General comments:

1.1 None of the authors was from the UK???

Author's response: We appreciate this reviewer's comments. One of our authors, Prof. Wafaa Saleh, is from Edinburgh Napier University, UK.

1.2 The authors should emphasize the significance of including these three types of crashes????

Author's response: We appreciate the reviewer's comments. We have incorporated the following statements into the introduction to underscore the significance of including the three crash types (please refer to lines 110 to 115; pages 5-6 in the manuscript):

“The study addresses a critical gap in current research, focusing on crashes specifically occurring on road segments. Existing literature offers limited insights into this specific type of crash, highlighting a crucial need for targeted investigation. These crashes have the potential for severe impact, involving complex dynamics that demand a nuanced understanding for effective mitigation strategies. By exploring these factors, our research aims to significantly enhance cyclist safety within this particular context.”

1.3 What novelty this study adds compared to the previous one in 2011???

Author's response:

We appreciate this reviewer's comment. One inherent problem with police-reported crash data is the variables not readily available, hereby causing unobserved heterogeneity across the observations. To overcome such a limitation, we estimated separate regression models, as suggested by Kim et al. (e.g., d), for the three crash types; such an approach provides greater explanatory power compared to single overall models. Further, we conducted joint-effect analyses of several variables of interest that capture heterogeneity. In our previous studies, we adopted the above-mentioned approaches to overcome the inherent problem with a success (e.g., e, f).

To clarify this, the following statements have been added to the Discussion section of the manuscript (please refer to lines 391 to 397; page 23 in the manuscript):

“One inherent problem with police-reported crash data is the variables not readily available, hereby causing unobserved heterogeneity across the observations. To overcome such a limitation, we estimated separate regression models, as

suggested by Kim et al. (e.g., d), for the three crash types; such an approach provides greater explanatory power compared to single overall models. Further, we conducted joint-effect analyses of several variables of interest that capture heterogeneity. In our previous studies, we adopted the above-mentioned approaches to overcome the inherent problem with a success (e.g., e, f).”

d: Kim, D., Washington, S., Oh, J., 2006. Modelling crash outcomes: new insights into the effects of covariates on crashes at rural intersections. *Journal of Transportation Engineering*. 132 (4), 282-292.

e: Pai CW, Jou RC, 2014. Cyclists’ red-light running behaviours: An examination of risk-taking, opportunistic, and law-obeying behaviours. *Accident Analysis and Prevention*. 62,191-198.

f: Pai CW, Saleh W., 2008. Modelling motorcyclist injury severity by various crash types at T-junctions in the UK. *Safety Science*. 13, 98-98.

1.4 The rationale for conducting the current study as well as the practical implications should be emphasized??

Author’s response: We appreciate this reviewer’s comments. First, regarding the rationale for conducting the current study, we have added the following statements (please kindly refer to lines 91-95 on page 5 of the manuscript):

“Bicycle crashes on road segments remain a substantial issue for public health concern. Existing research primarily emphasizes intersection-related crashes. This study aims to fill a critical gap by conducting a thorough examination of the risk factors associated with three distinct bicycle crash types: overtaking, rear-end, and door crashes that occur on road segments.”

Secondly, to highlight the practical implications, we have included the following statements in the Discussion section (please refer to lines 404-412 on pages 23-24 of the manuscript):

“Recommendations

For overtaking crashes, we recommend implementing 'Share the Road' warning signs, especially in rural areas, and developing specialized cognitive training programs for elderly drivers. Regarding rear-end crashes, our suggestions include improving illumination during night time and implementing speed control measures on rural road segments. For door crashes involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility. Moreover, implementing a two-stage door opening mechanism and an automatic

detection device in vehicles to alert drivers of bicycles approaching from behind could potentially be beneficial.”

1.5 For the introduction section, burden in terms of mortality, morbidity, and DALYs should be mentioned as well the economic and health care costs should be mentioned (globally and UK)

Author’s response: We appreciate the reviewer’s comments. Our original literature review has included several past studies that have reported the accident/injury outcomes resulting from these three crash types. For example, road segments with elevated speed limits, male cyclists, and cyclists aged over 55 years contribute significantly to high injury severity crashes. Additionally, built-up areas increase the risk of door crashes involving cyclists and parked cars.

It is important to note that there is limited research specifically examining the impact of overtaking, rear-end, and door crashes on Disability-Adjusted Life Years DALYs, economic costs, and healthcare expenses. Notable exceptions include studies by Elvik and Sundfør (e.g., d), who examined the inclusion of cyclist injuries in health impact economic assessments. Aertsens et al. (e.g., h) and Scholten et al. (e.g., i) also provided comprehensive analyses of the total and average costs associated with bicycle injuries. Although the three crash types were not explicitly examined in the above-mentioned studies, we have followed this reviewer’s suggestion by incorporating these studies into the 'Introduction' section (please refer to lines 77-81; page 4 of the manuscript):

“Bicycle crashes can also impose a significant burden on healthcare expenses. Elvik and Sundfør (e.g., g) have discussed the economic implications and healthcare expenditures associated with bicycle accidents. For instance, in Belgium, the average cost of bicycle accidents per case is estimated at 841 euros (e.g., h). In the Netherlands, the total annual cost has been reported as €410.7 million (e.g., i).”

References:

- g: Elvik, R., & Sundfør, H. B. (2017). How can cyclist injuries be included in health impact economic assessments? *Journal of Transport & Health*, 6, 29-39.
- h: Aertsens, J., de Geus, B., Vandenbulcke, G., Degraeuwe, B., Broekx, S., De Nocker, L., ... & Panis, L. I. (2010). Commuting by bike in Belgium, the costs of minor accidents. *Accident Analysis & Prevention*, 42(6), 2149-2157.

i: Scholten, A. C., Polinder, S., Panneman, M. J., Van Beeck, E. F., & Haagsma, J. A. (2015). Incidence and costs of bicycle-related traumatic brain injuries in the Netherlands. *Accident Analysis & Prevention*, 81, 51-60.

1.6 The number of cyclists in UK or those using bicycles for their mobility??

Author's response: We appreciate the reviewer's comment. In our study, we analyzed national police-reported crash data involving cyclists. Unfortunately, exposure data, such as the number of cyclists and miles traveled, were not available in the STATS19 dataset. While such data may be available from the UK National Travel Survey, it often reflects outdated information and may not be fully representative of the entire population.

2. Specific comments:

2.1 Instead of data collection, data used for analysis is appropriate??

Author's response: We appreciate the reviewer's comment. The dataset, UK Stats19 covering all traffic accidents in the UK, should be appropriate, as numerous studies in the field of traffic injury and medicine have analysed such data (e.g., references j, k, l).

j: Haghpanahan, Houra, et al. "An evaluation of the effects of lowering blood alcohol concentration limits for drivers on the rates of road traffic accidents and alcohol consumption: a natural experiment." *The Lancet* 393.10169 (2019): 321-329.

k: Pai, C. W., Hwang, K. P., & Saleh, W. (2009). A mixed logit analysis of motorists' right-of-way violation in motorcycle accidents at priority T-junctions. *Accident Analysis & Prevention*, 41(3), 565-573.

l: Fountas, G., Fonzone, A., Gharavi, N., & Rye, T. (2020). The joint effect of weather and lighting conditions on injury severities of single-vehicle accidents. *Analytic methods in accident research*, 27, 100124.

2.2 Of the used crashes data, how many were fatal???

Author's response: We appreciate the reviewer's comment. As reported in the table below, as many as 0.8% of those in overtaking crashes sustained fatal injuries, which was the highest compared to those in the other two crash types.

	Slight	Serious	Fatal	Total
Overtaking crashes	14240(77.6%)	3,964(21.6%)	147(0.8%)	18350

Rear-end crashes	39821(89.1%)	4782(10.7%)	89(0.2%)	44692
Door crashes	5561(87.4%)	770(12.1%)	32(0.5%)	6363

2.3 For analysis of data, use the Odds ratios and 95% confidence intervals (univariate and bivariate)

Author's response: We appreciate this reviewer's comment. We analyzed the distribution of crash types across a set of independent variables. Chi-square tests were used to explore relationships between these variables and crash types. Variables with a significance level below 0.2 were identified to minimize type II errors and were considered significantly associated with the outcome variables ($p < 0.05$). Subsequently, these variables were included in multiple logistic regression models. Stepwise logistic regression was then employed to estimate the odds of various variables after controlling for specific factors. This methodology has been widely used in past studies of traffic injuries (e.g., a, b) and methodology (e.g., c).

a: Chen, P-L, Pai, C-W. Evaluation of injuries sustained by motorcyclists in approach-turn crashes in Taiwan. *Accident Analysis and Prevention*, 2019, 124, 33-39;

b: Chien, D-K., Hwang, HF, Lin, MR. Injury severity measures for predicting return-to-work after a traumatic brain injury. *Accident Analysis and Prevention*, 2017, 98, 101-107;

c: Maldonado G, Greenland S. Simulation study of confounder-selection strategies. *Am J Epidemiol* 1993, 138, 11, 923-936).

2.4 Details about the multivariate logistic regression model should be mentioned???

Use the Odds ratios for interpreting and displaying the results in tables 1, 2, and 3???

Author's response: We appreciate the reviewer's comment. Firstly, if we understand this reviewer correctly, we have incorporated additional details (such as formulation and derivation) of the multivariate logistic regression model into the "Methods" section (please refer to lines 179-194 on pages 10-11 of the manuscript):

"Initially, we examined the distribution of three crash types across various variables to explore their relationships with a binary outcome. These variables included lighting conditions, speed limit, time of day, and day of the week. Demographic details concerning cyclist casualties encompassed age and sex, while information about the crash partner included vehicle type, age, and sex. We set a significance level of $p <$

0.2 to include risk factors in our multivariate analysis. Adjusted odds ratios (AORs) were computed using multivariate logistic regression with backward selection.

The multivariate logistic regression model equation was specified as:

$$\log\left(\frac{P(Y = 1)}{1 - P(Y = 1)}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2$$

where $P(Y = 1)$ denotes the probability of the outcome, $\beta_0, \beta_1, \beta_2, \dots, \beta_p$ are the coefficients to be estimated, and X_1, X_2, \dots, X_p represent the predictor variables.

Before estimating the model, assumptions of logistic regression, such as linearity of the logit, absence of multicollinearity, and independence of observations, were evaluated.

An odds ratio (OR) greater than 1 indicated a positive association between the independent variable and the occurrence rate, while an OR less than 1 indicated a negative association. An OR of 1 suggested no association between the variables of interest and the outcomes.”

Secondly, this reviewer suggested that we should use the Odds ratios for interpreting and displaying the results in tables 1, 2, and 3. While we acknowledge this suggestion, we would like to clarify here that we adopted the commonly-used Chi-square tests to identify the distribution of three crash types across several independent variables. Instead of the univariate logistic regression, such a method has been proved as an efficient way to minimize type II errors, and has been widely employed in past studies of traffic injuries (e.g., a, b) and methodology (e.g., c).

a: Chen, P-L, Pai, C-W. Evaluation of injuries sustained by motorcyclists in approach-turn crashes in Taiwan. *Accident Analysis and Prevention*, 2019, 124, 33-39;

b: Chien, D-K., Hwang, HF, Lin, MR. Injury severity measures for predicting return-to-work after a traumatic brain injury. *Accident Analysis and Prevention*, 2017, 98, 101-107;

c: Maldonado G, Greenland S. Simulation study of confounder-selection strategies. *Am J Epidemiol* 1993, 138, 11, 923-936).

2.5 Chi square is not enough test to identify the direction and which segment of the given variable is significantly different???

Author's response: We appreciate this reviewer's comment. The reviewer is correct. Chi-square tests can be used for ascertaining the association of the dependent and independent variables. However, the direction of the independent variables can be untangled in the subsequent multivariate logistic regression models.

2.6 What was the adjustment made for??? And how???

Author's response: We appreciate this reviewer's comment. Each variable was adjusted for in the multivariate analysis. For instance, in Table 4, adjustments were made for crash day after accounting for other variables such as cyclist's sex, crash partner, and crash partner's age and sex.

2.7 The joint-crash effect: how it was measured statistically???

Author's response: Thank you for your valuable comment. We do apologize for not making our analysis clear. To clarify how joint-effect analysis was structured, we drew several figures below that help us respond to this reviewer.

As Figure A1 (X axis: speed limit; Y axis: percentage) and A2 report (X axis: Crash partner's age; Y axis: percentage), the joint effects of speed limit (two categories: rural (≥ 40 mph) /urban (20–30 mph)] and crash partner's age (four categories: ≤ 18 , 19–40, 41–64, and ≥ 65) on overtaking crashes were examined, yielding eight combinations of interaction effects (i.e., 1. Rural x ≤ 18 ; 2. Rural x 19-40; 3. Rural x 41-64; 4. Rural x ≥ 65 ; 5. Urban x ≤ 18 ; 6. Urban x 19-40; 7. Urban x 41-64; 8. Urban x ≥ 65). All percentages of overtaking crashes among these eight combinations were compared, and the combination with the highest percentages for overtaking crashes is taken as the indicator variable. In this joint-effect analysis, the indicator variable "rural areas x crash partner's ≥ 65 years old" has the highest percentage of overtaking crashes. These results elucidated that overtaking crashes were more likely to occur when the cyclists were in rural areas and when involving ≥ 65 -year-old crash partners.

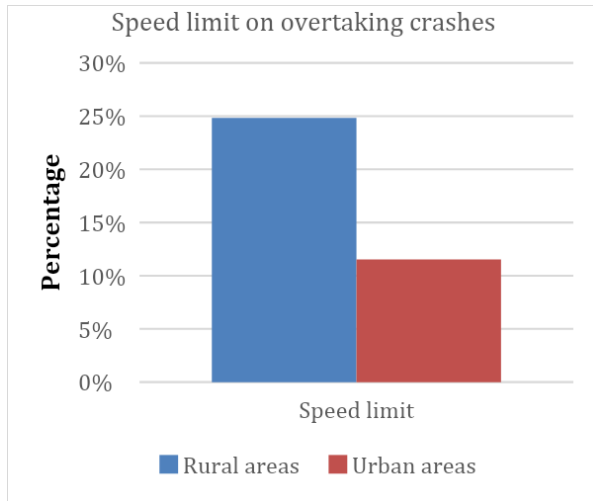


Figure A1

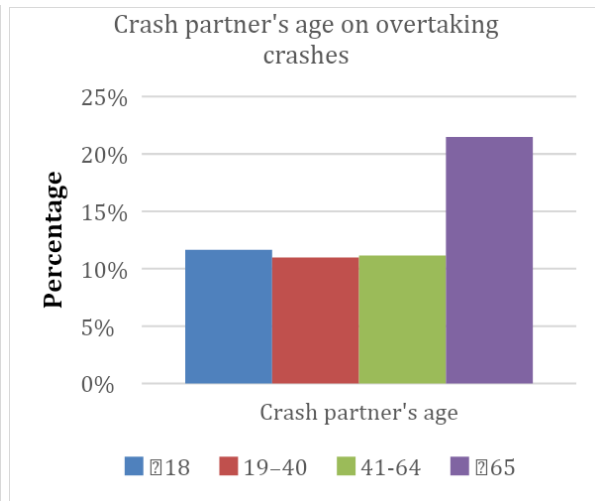
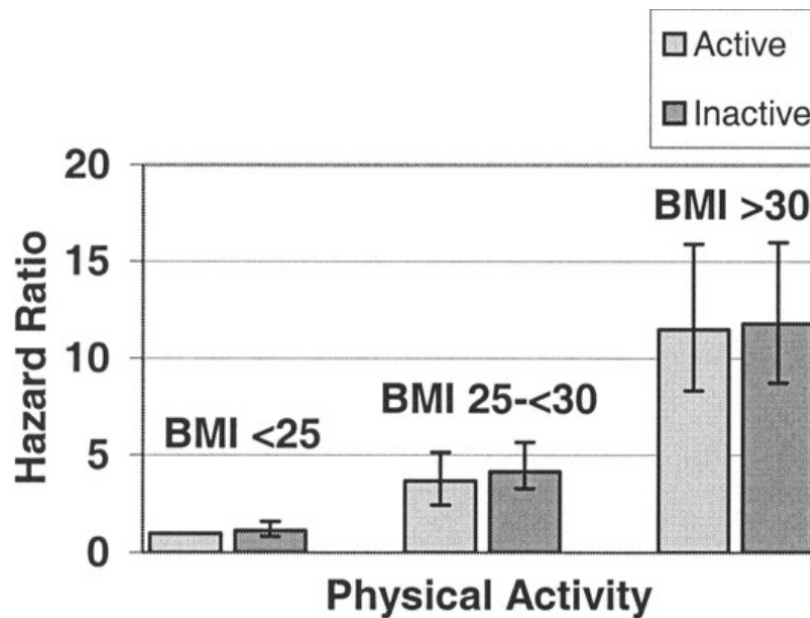


Figure A2

In practice, such a joint-effect analysis has been widely employed in medicine or traffic injury literature. One well-known paper by Weinstein et al. (i.e., m) was published in JAMA which examined the joint effect of physical activity and body mass index on diabetes in women. In this paper, Weinstein et al. pointed out that the beneficial effect of active lifestyle on type 2 diabetes was consistent across women with three BMI levels.



Another example is our previous paper published in Accident Analysis and Prevention in 2020 titled: Evaluating the combined effect of alcohol-involved and un-helmeted riding on motorcyclist fatalities in Taiwan. In this study, we specifically analysed the joint effect of alcohol use and helmet use on motorcyclist fatalities (i.e., n).

Interaction results for motorcyclist’s alcohol use with motorcyclist’s helmet use.

Interaction term	Odds ratio	p value	95 % CI
Blood alcohol level with helmet use ^a			
1 Blood alcohol positive and not using helmet	18.1	< 0.001	15.9 – 20.4
2 Blood alcohol positive and using helmet	10.1	< 0.001	9.3 – 11.1
3 Blood alcohol negative and not using helmet	2.3	< 0.001	2.1 – 2.5
4 Blood alcohol negative and using helmet	1	–	1

In addition, our previous paper published in BMC Public Health in 2023 titled: Walking against traffic and pedestrian injuries in the United Kingdom: new insights (i.e., o). In this study, we specifically analysed the joint effect to examine whether the beneficial effect of walking against traffic on injury severity may apply to different situations. By doing so, we were able to compare injury outcomes in walking against-traffic crashes against those in walking with-traffic crashes.

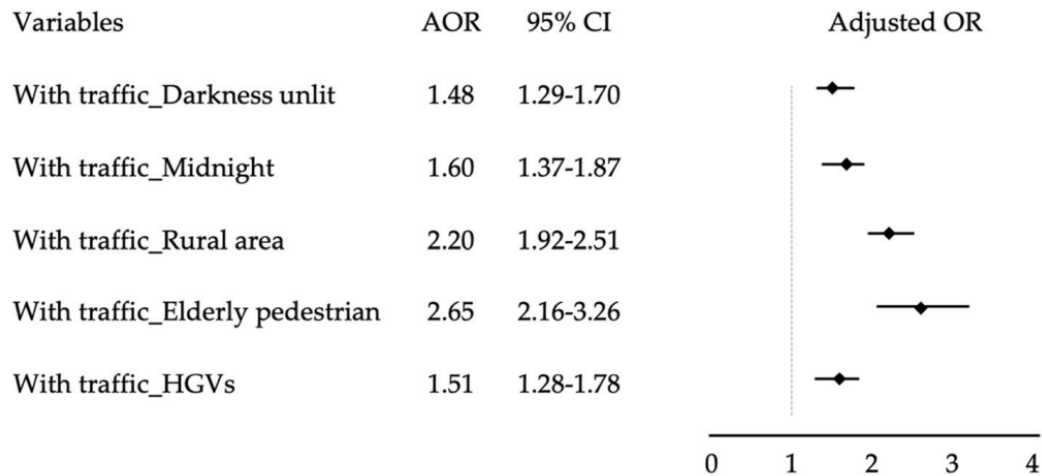


Fig. 2 Joint effects of walking with traffic and other variables on pedestrian fatalities

We believe this detailed explanation clarifies our methodology.

Reference:

m: Weinstein A., Sesso, H., Lee, I., Cook, N., Manson, J., Buring, J., Gaziano, J., 2004. The relationship of physical activity vs body mass index with type 2 diabetes in women. JAMA 290: 1188-1194.

n: Wiratama, B., Chen, P., Ma, S., Chen, Y., Saleh, W., Lin, H., Pai, C., 2020. Evaluating the combined effect of alcohol-involved and un-helmeted riding on motorcyclist fatalities in Taiwan. Accident Analysis and Prevention, 143, 105594.

o: Widodo, A. F., Chen, C., Chan, C. W., Saleh, W., Wiratama, B. S., & Pai, C. W. (2023). Walking against traffic and pedestrian injuries in the United Kingdom: new insights. BMC public health, 23(1), 2205.

Reviewer #3: Areas for Improvement:

3.1 Clarity and Conciseness:

Some sections of the text are verbose and could benefit from more concise language. For instance, the detailed descriptions of statistical methods and results could be streamlined without losing essential information.

Simplifying the language and structure would enhance readability and accessibility, particularly for readers who are not specialists in the field.

Author's response: We appreciate the reviewer's valuable suggestions. Concerning two reviewers who recommended extending several sections (i.e., reviewer #2 asked us to explain more on multivariate regression models and reviewer #4 requested for further discussions), we maintained a neutral stance for the time being. Nonetheless, we have revised the introduction to provide a clearer context and expanded our descriptions in the discussion section to provide broader insights into the implications of our findings. Additionally, detailed descriptions of the statistical methods have been included in the methods section, aimed at enhancing readability and accessibility for our readers.

3.2 Detailed Interpretation of Results:

While the results section provides extensive data, there is limited interpretation of what these results mean in practical terms. Adding more context about how these findings could influence policy or infrastructure design would be valuable. Discussing potential interventions based on the identified risk factors, such as specific infrastructure improvements or policy changes, would strengthen the practical implications of the study.

Author's response: We appreciate the reviewer's comment and suggestion. We have revised the discussion section of the manuscript and added one recommendation section to address findings that could potentially influence policy or infrastructure as follows (please refer to lines 404-412 on pages 23-24 of the manuscript):

"Recommendations

For overtaking crashes, we recommend implementing 'Share the Road' warning signs, especially in rural areas, and developing specialized cognitive training programs for elderly drivers. Regarding rear-end crashes, our suggestions include improving illumination during night time and implementing speed control measures on rural road segments. For door crashes involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility. Moreover, implementing a two-stage door opening mechanism and an automatic

detection device in vehicles to alert drivers of bicycles approaching from behind could potentially be beneficial.”

3.3 Comparative Analysis:

Including a comparative analysis with similar studies from other countries could provide a broader context for the findings and highlight whether these risk factors are unique to the UK or consistent globally.

Discussing how the UK’s findings compare with those from the United States or other European countries, especially concerning the impact of infrastructure and vehicle types, could offer valuable insights:

Author’s response: We appreciate the reviewer’s comment. To our knowledge, no comparative analysis from other countries has been conducted for the three crash types (overtaking, rear-end, and door crashes). In addition, it is out of the scope of the current research to obtain crash data from other countries and conduct a large scale of comparative analysis. However, in our introduction sections, we have reviewed previous studies that focused on risk factors for these crash types individually or collectively on road segments (such as vehicle volume, traffic density, and number of lanes).

In the discussion section, we have discussed our findings with those of other studies in the US or elsewhere. For instance, previous analyses of overtaking crashes highlighted risk factors such as speeds exceeding 10 mph and the presence of pick-up trucks. Rear-end crashes were associated with conditions such as darkness, unlit surroundings, midnight hours, and reduced cognitive capabilities. Door crashes were found to be influenced by factors including urban roadways and the presence of taxis.

3.4 Providing more detailed information about the methodology, particularly the criteria for excluding certain data points, would enhance transparency. For example, explaining why specific demographic data were incomplete and how this might affect the results would be useful.

A discussion on the limitations of the data and the potential biases introduced by police reporting practices could provide a more nuanced understanding of the findings.

Author’s response: We appreciate the reviewer’s comment. To clarify the reasons for excluding junction cases and cyclists/motorcyclists as crash partners, we have added the following statements in the Methods section (please also kindly see lines 168 to 174; pages 9-10 in the manuscript):

“On a cautionary note, we removed junction cases to avoid the variability introduced when exogenous factors, such as junction geometry and control measures, are present at junctions. Furthermore, the cases involving other cyclists and motorcyclists were removed as we focused on vehicle-cycle crashes only. Missing data on sex, age, or speed limits were also excluded in the analysis. Excluding these data may impact our results in a marginal scale, as these data are likely to be single-bicycle crashes that in nature be underreported in police crash dataset [e.g., p]. “

Regarding the limitation of police reported crash data, the following statements have been added to the manuscript (please also kindly see lines 378 to 391; pages 22-23 in the manuscript):

“This study had several limitations that warrant acknowledgement. First, the substantial underreporting of nonfatal casualties to the police, particularly casualties involving cyclists not obligated to report accidents, is a critical factor to consider. Such underreporting, as highlighted by the U.K. Government’s Department for Transport, likely results in the incomplete representation of nonfatal and ‘slight’ casualties in road casualty data. Second, the STATS19 data utilised in this study lack critical variables, including precrash speeds, specific geometric characteristics of roadways, data regarding alcohol and illicit substance use, and cyclist speed at the time of an accident. Moreover, critical exposure data—such as those related to traffic flow, rider or driver experience, and other elements of risk exposure—are absent, and the absence of such details limits our ability to fully account for potential variations resulting from unobserved factors in the analyses. Finally, this study did not explore annual trends in each type of bicycle crash over the 30-year study period; investigating such trends could provide insights regarding changing behaviours among cyclists and motor vehicle drivers as well as the effects of legislative changes for road speed limits.”

p. Watson, Angela, Barry Watson, and Kirsten Vallmuur. "Estimating under-reporting of road crash injuries to police using multiple linked data collections." *Accident Analysis & Prevention* 83 (2015): 18-25.

3.4 Visual Aids:

Adding more visual aids, such as graphs or charts, could help in visualizing the key findings and making the data more accessible to readers.

A geographic distribution map showing where different types of crashes are more prevalent could add an interesting dimension to the analysis.

Author's response: We appreciate the reviewer's suggestions. We firstly reported our sampling by using a flowchart that helps readers understand what data were excluded and included in the analyses. Although we presented our statistical analyses in a traditional way (Tables 1 to 4), we illustrated a forest plot demonstrating the joint effects of several variables on the three crash types when other variables were controlled for (please refer to lines 213 to 276; pages 12-17 in the manuscript).

Regarding the geographic distribution map illustrating where these crash types were more prevalent, our research objective does not primarily emphasize the geographic effects of these three crash types. Rather, we focused on identifying risk factors for these crash types. While we appreciate this reviewer's valuable comment on this, we have identified this as an important research area as follows (please refer to lines 398 to 402; page 23 in the manuscript):

“Future research directions could involve integrating GPS (Global Positioning System) data and weather conditions to analyse both the injury frequency and fatalities of bicycle crashes on road segments. Additionally, exploring the potential of autonomous vehicles for detecting approaching bicycles for door-crashes and implementing AI-controlled lighting systems in rural areas for cyclist detection could be promising areas for further study.”

3.5 Future Directions:

Including a section on future research directions would be beneficial. Identifying gaps in the current research and suggesting areas for further investigation could guide subsequent studies.

Discussing the potential impact of emerging technologies, such as autonomous vehicles and advanced cyclist detection systems, on these crash types could provide a forward-looking perspective.

Author's response: We appreciate the reviewer's comment and suggestion. We have revised the discussion section of the manuscript and added one future research section (please refer to lines 398 to 402; page 23 in the manuscript). Furthermore, we have added one new section “Recommendation” that reports potential intervention points (please refer to lines 404-412 on pages 23-24 of the manuscript):

“Recommendations

For overtaking crashes, we recommend implementing 'Share the Road' warning signs, especially in rural areas, and developing specialized cognitive training programs for elderly drivers. Regarding rear-end crashes, our suggestions include improving illumination during night time and implementing speed control

measures on rural road segments. For door crashes involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility. Moreover, implementing a two-stage door opening mechanism and an automatic detection device in vehicles to alert drivers of bicycles approaching from behind could potentially be beneficial.”

Future research directions:

“Future research directions could involve integrating GPS (Global Positioning System) data and weather conditions to analyse both the injury frequency and fatalities of bicycle crashes on road segments. Additionally, exploring the potential of autonomous vehicles for detecting approaching bicycles for door-crashes and implementing AI-controlled lighting systems in rural areas for cyclist detection could be promising areas for further study.”

Reviewer #4: This Study is technically sound and has potential to add to the body of knowledge involving bicycle riding safety in the UK and everywhere across the globe. It has adhered to the research and publication ethics, however, the study still need revision on some of the key identified areas which i have pointed out, starting from abstract, background, results and discussions.

4.1 Abstract

The abstract is lacking the background section, please see the comment on the pdf

This abstract is lacking the background section, which must start when presenting structured abstract. Also there is no objective put here, but rather the research problem investigated.

Author's response: We appreciate the reviewer's comment and suggestion. We have revised the abstract to add background and objects as follows (please refer to lines 23 to 27; page 2 in the manuscript):

“Background: Relevant research has provided valuable insights into risk factors for bicycle crashes at intersections. However, few studies have focused explicitly on three common types of bicycle crashes on road segments: overtaking, rear-end, and door crashes.

Objective: This study aims to identify risk factors for overtaking, rear-end, and door crashes that occur on road segment.”

4.1.1 Abbreviations should be defined when they are first mentioned

Author's response: We appreciate the reviewer's suggestion. We have revised the abstract to include the full definitions of abbreviations upon their first appearance as follows (please refer to lines 31; page 2 in the manuscript).

“Abstract: AOR (adjusted odds ratio)”

4.2 Introduction

4.2.1 The authors did not explain the context of the previous study, where this current study was based, but only cited it. For my comments also see the pdf with my comments on this section

4.2.2 See the comments above on the abstract to enhance this one

4.2.3 Highlight some key findings of this previous study here to avoid making the readers look for the findings on their own. The point of scientific writing is to make the work easy to understand

Author's response: We appreciate the reviewer's comment and suggestion. We have revised our introduction section to include the reviewer's suggestion, providing an explanation of the previous study and emphasizing our key findings accordingly as follows (please refer to lines 101 to 106; page 5 in the manuscript):

“The primary objective of this study, building on our previous research into risk factors related to overtaking, rear-end, and door crashes, is to conduct a more comprehensive investigation. Specifically, Pai identified buses and coaches as common crash partners in overtaking crashes; poor visibility, traversing manoeuvres, and teenage cyclists as risk factors for rear-end crashes; and built-up areas as a risk factor for door crashes.”

4.3 Methodology

The method section was described well and is adequate, although we need to know whether normality checks were conducted.

Author's response: Thank you for your positive feedback on the method section and for your valuable suggestion regarding normality checks. We employed multivariate logistic regression models in our investigation, which do not require assuming the normality of the predictor variables. Logistic regression is resilient to deviations from normality as it estimates the likelihood of a binary outcome instead of assuming a normal distribution of the variables. Consequently, we refrained from performing formal normality assessments for the predictor variables.

4.4 Results

This area still requires more work. The way the results were presented was hasty, and we need to redo some of the highlighted sections. For example, a separate Univariate table is needed as Table 1.

4.4,1 I think you need a joint univariate table of all factors studied that combining it all in the Bivariate table. It is a lazy way of reporting that require a reader to tease out proportions on their own. address this

Author's response: We appreciate the reviewer's comment. In response to the suggestion for a joint univariate table of all studied factors, we acknowledge the importance of presenting comprehensive data that is readily interpretable. Our analysis

included an examination of crash type distributions across multiple independent variables. To explore these relationships, we employed Chi-square tests. Variables with significance levels below 0.2 were identified to minimize type II errors and were considered significantly associated with the outcome variables ($p < 0.05$). These variables were subsequently included in multiple logistic regression models.

We utilized stepwise logistic regression to estimate odds ratios while controlling for specific factors, following a methodological approach well-established in traffic injury studies (e.g., references a and b) and detailed in previous research (e.g., reference c). This approach allows for a nuanced understanding of how various factors interact to influence crash types, ensuring our findings are robust and informative. This methodological approach is well-established in the study of traffic injuries (e.g., references a and b) and has been detailed in previous studies (e.g., reference c).

a: Chen, P-L, Pai, C-W. Evaluation of injuries sustained by motorcyclists in approach-turn crashes in Taiwan. *Accident Analysis and Prevention*, 2019, 124, 33-39;

b: Chien, D-K., Hwang, HF, Lin, MR. Injury severity measures for predicting return-to-work after a traumatic brain injury. *Accident Analysis and Prevention*, 2017, 98, 101-107;

c: Maldonado G, Greenland S. Simulation study of confounder-selection strategies. *Am J Epidemiol* 1993, 138, 11, 923-936).

4.4.2 Use one decimal place and not two

Author's response: We appreciate this reviewer's comment. We have updated our tables (Tables 1-4) to display data with one decimal place instead of two (please refer to lines 213 to 276; pages 12-17 in the manuscript).

4.4.3 After inserting a combined univariate table, please remove these percentages, as they are very misleading

Author's response: We appreciate this reviewer's comment. However, presenting percentages is crucial for demonstrating the distribution among each crash type and others. Therefore, we have decided to continue using percentages as presentation in our manuscript.

4.4.5 Tables: Here put frequencies/percenatgase and removed all the percentages from the table. the same applies to all other tables

Author's response: We appreciate this reviewer's comment. Nevertheless, it is essential to use percentages to clearly demonstrate the distribution of each crash type across a set of variables. By reporting these percentages, we are able to identify whether one certain variable was over-involved in one crash type. Therefore, we have opted to maintain the use of percentages in our presentation.

4.4.6 All most all the bivariate table has not been interpreted. but summarize using phrases like serveral variables as shown in table 2.

Author's response: We appreciate this reviewer's comment. We have revised our results section to incorporate the reviewer's suggestion and rephrase the sentence accordingly (please refer to lines 215 to 229; page 13 in the manuscript):

"Several variables in Table 2 reveal significant differences between rear-end crashes and non-rear-end crashes. Specifically, a higher proportion of rear-end crashes occurred under darkness-unlit conditions (50.2%) compared to darkness-lit conditions (37.5%). Additionally, rear-end crashes were more prevalent in rural areas with speed limits of ≥ 40 mph (43.0%) compared to urban areas with speed limits of 20–30 mph(33.1%). Crashes involving crash partners aged ≥ 65 accounted for 39.7% of rear-end crashes, which was higher compared to other age groups (age 41–64: 33.0% and ≤ 18 : 36.0%). Furthermore, rear-end crashes were more likely to occur during midnight (47.6%) compared to rush hours (36.3%). Taxis were frequently involved in rear-end crashes (42.4%), as were male crash partners (36.8%). These findings highlight the significant influence of various factors on the likelihood of rear-end crashes. Variables such as darkness-unlit conditions, higher speed limits in rural areas, crash time, and characteristics of the crash partner all emerged as significant determinants. Specifically, rear-end crashes were notably more prevalent under darkness-unlit conditions, in rural areas with higher speed limits, during midnight hours, and involving certain characteristics of crash partners. Importantly, these associations were statistically significant, as indicated by the Chi-squared test ($p < 0.001$)."

4,4,7 Do inteprete the results individually for all the significant factors.

Author's response: We appreciate this reviewer's comment. We have revised our discussion section to incorporate the reviewer's suggestion and rephrase the sentence accordingly (please refer to lines 232 to 248; pages 14-15 in the manuscript):

"As shown in Table 3, several variables can contribute to door crashes involving bicycles. Door crashes predominantly occurred in urban areas with speed limits of 20-30 mph (6.22%), while a significantly lower proportion occurred in rural

areas with speed limits ≥ 40 mph (0.45%). These crashes were overrepresented during non-rush hours (5.54%) and rush hours (4.94%) compared to evening (4.26%) and midnight (2.35%). Cyclists were more frequently involved in door crashes on weekdays (5.35%) than weekends (3.73%). As many as 8.21% of all female cyclists were involved in door crashes, which is higher than the involvement rate among males (4.24%). Taxi and private hire cars were overinvolved in door crashes (10.55%) compared to cars (5.17%) and buses/heavy goods vehicles (3.13%). Crash partners aged ≤ 18 years (5.22%) and 19-40 years (5.26%) were disproportionately involved in door crashes compared to older age groups, and female crash partners were overrepresented in door crashes (7.42%) compared to males (4.23%). These results were statistically significant, as indicated by the Chi-squared test ($p < 0.001$). They suggest that various factors including traffic conditions (rural areas, crash time), cyclist demographics (younger age, gender), and characteristics of the crash partner (taxi/private hire cars)—significantly contribute to the likelihood of door crashes involving cyclists.”

4.4.8 where are the corresponding p-values. include them for all the significant risk factors

Author’s response: We appreciate this reviewer’s comment. We have revised our Results section to include the reviewer’s suggestion and have added the corresponding p-values accordingly (please refer to lines 253 to 272; page 16 in the manuscript):

For example: “(AOR = 2.912, 95% CI = 2.384–3.556; $p < 0.001$).”

4.4.9 Here, present both the crude and adjusted odd ratios

Author’s response: We appreciate the reviewer’s comment. In response, we have focused on presenting the adjusted odds ratios (AOR) and their corresponding 95% confidence intervals in our manuscript.

To address the analysis of crash types across various independent variables, we conducted Chi-square tests to assess the association between dependent and independent variables. The direction of the independent variables will be clarified in the subsequent multivariate logistic regression models.

Significant variables identified through stepwise selection were included in the multiple logistic regression models. The adjusted odds ratios (AOR) and their 95% confidence intervals were then calculated from these final models. This approach, widely used in traffic injury studies (e.g., a, b), ensures robust methodology by controlling for other variables (e.g., c).

a: Chen, P-L, Pai, C-W. Evaluation of injuries sustained by motorcyclists in approach-turn crashes in Taiwan. *Accident Analysis and Prevention*, 2019, 124, 33-39;

b: Chien, D-K., Hwang, HF, Lin, MR. Injury severity measures for predicting return-to-work after a traumatic brain injury. *Accident Analysis and Prevention*, 2017, 98, 101-107;

c: Maldonado G, Greenland S. Simulation study of confounder-selection strategies. *Am J Epidemiol* 1993, 138, 11, 923-936).

4.4.10 Also do interpret these results. For instance what does the odd ratio of 2.93 mean in this case?

Author's response: We appreciate the reviewer's comment and suggestion. We have revised our results section to incorporate the reviewer's suggestion and have interpreted the meaning of odds ratios in our findings accordingly (please refer to lines 279 to 286; pages 17-18 in the manuscript):

"The results identified several key risk factors for both overtaking and rear-end crashes. The risk of overtaking crashes showed a significant increase of 193% in rural areas when elderly drivers were involved (AOR = 2.93, 95% CI = 2.79–3.08), and similarly when heavy goods vehicles (HGVs) were the crash partner (AOR = 2.62, 95% CI = 2.46–2.78). Elderly cyclists also faced a higher risk of overtaking crashes on weekends (AOR = 1.56, 95% CI = 1.34–1.81).

Regarding rear-end crashes, the risk increased notably with unlit darkness during midnight (AOR = 1.68, 95% CI = 1.48–1.90) and was significantly higher in rural areas (AOR = 2.15, 95% CI = 2.01–2.31)."

4.4.11 you look at risk factors and not only environment factors, what about factors like sex, age. are they from the environment too, and yet you included them.

Author's response: We appreciate the reviewer's comment. In our multivariate logistic regression results in Table 4, we analyzed and presented such factors such as cyclist's sex and age for each crash type (please refer to lines 275 to 276; page 17 in the manuscript). Moreover, in our joint-effect analysis, cyclist's age (≥ 65 -year-old cyclist) was combined and analyzed with other variables.

4.5 Discussion

The section also needs serious work, especially on the way the findings were discussed. The authors should consider discussing their own findings rather than those of other studies. There is also a need to have a section for recommendations rather than merging it within result

4.5.1 You dont need this type of writing, just discuss the findings

Author's response: We appreciate the reviewer's comment. We have revised our discussion section to delete the paragraph as the reviewer's suggestion as follows (please refer to lines 305; page 19 in the manuscript):

“Delete: These findings warrant further discussion and thus are elaborated on in this section of this paper.”

You have not discussed the findings. Yes you found HGVs a risk for overtaking crash, so tell us why you think that is a risk factor. in other word explain your findings and then place it in the context of other study

Author's response: We appreciate the reviewer's comment and suggestion. We have revised our discussion section to integrate the reviewer's suggestion and provide a discussion on how heavy goods vehicles (HGVs) pose a risk for overtaking crashes accordingly as follows (please refer to lines 308 to 317; page 19 in the manuscript):

“These findings align with previous research that identified elderly drivers, speeds exceeding 10 mph, and the presence of pick-up trucks as factors contributing to increased risk for overtaking crash. Specifically, HGVs possess several characteristics that amplify this danger. Their large blind spots make it difficult for drivers to see cyclists, increasing the likelihood of crashes during overtaking. Additionally, HGVs are less maneuverable compared to passenger cars, which reduces their ability to avoid crashes if cyclists suddenly enter their path. The speed and distance perception issues between HGVs and cyclists further complicate the judgment of safe overtaking gaps. Furthermore, HGVs require longer stopping distances due to their size and weight, which can lead to severe consequences if a sudden need to brake arises.”

4.5.3 Do not discuss other people's findings, just discuss your findings and only state whether it agrees or disagrees with what Pai et al found for example

Author's response: We appreciate the reviewer's comment and suggestion. We have revised our Discussion section to incorporate the reviewer's suggestion and provide a

discussion on our findings, comparing them with previous studies accordingly (please refer to lines 318 to 322; pages 19-20 in the manuscript):

“Regarding the association with buses or HGVs, our findings are consistent with existing research suggesting that time pressures on HGV drivers for timely loading and unloading might lead to more reckless driving. Specifically, our results align with the observations made by Pai et al., who also mentioned higher crash rates involving buses or HGVs, supporting the idea that these time pressures contribute to increased crash risks.”

4.5.4 Take this to the recommendation section

Author’s response: We appreciate the reviewer’s comment and suggestion. We have added a recommendations section (please refer to lines 404-412; pages 23-24 of the manuscript):

“Recommendations

For overtaking crashes, we recommend implementing 'Share the Road' warning signs, especially in rural areas, and developing specialized cognitive training programs for elderly drivers. Regarding rear-end crashes, our suggestions include improving illumination during night time and implementing speed control measures on rural road segments. For door crashes involving parked cars, we propose enhancing driver sight triangles and increasing cyclist visibility. Moreover, implementing a two-stage door opening mechanism and an automatic detection device in vehicles to alert drivers of bicycles approaching from behind could potentially be beneficial.”

4.5.5 Good use of references but first tells why you found what you found. And again your study was looking at comparing the risk factors for overtaking crashes with what was previously found in your study and the findings of that study needed to be described well in this study too

Author’s response: We appreciate the reviewer’s comment and suggestion. We have revised our Discussion section to incorporate the reviewer's suggestion and provide a discussion on our findings, comparing them with previous studies accordingly (please refer to lines 328 to 332; page 20 in the manuscript):

“We found that as individuals age, their risk of being involved in road accidents increases, primarily due to declines in cognitive capabilities. Our study corroborates these findings by showing that older cyclists are more susceptible to accidents during overtaking maneuvers, which can be attributed to diminished reaction times and impaired decision-making abilities, their health, and their driving performance.”

4.5.6 I think you need to also link this to delays in reacting as compared to the younger cyclist or driver.

Author's response: We appreciate this reviewer's comment. We have revised our Discussion section to integrate the reviewer's suggestion and provide a discussion on delays in reaction among elderly cyclists or drivers accordingly (please refer to lines 328 to 332; page 20 in the manuscript):

“We found that as individuals age, their risk of being involved in road accidents increases, primarily due to declines in cognitive capabilities. Our study corroborates these findings by showing that older cyclists are more susceptible to accidents during overtaking maneuvers, which can be attributed to diminished reaction times and impaired decision-making abilities, their health, and their driving performance.”

4.5.7 This is supposed to be a recommendation but first of all it is not right. it is not what you found but what you think is making more elder drivers to get into overspreading crashes. So recommend only based on what you found and not based on what you think.

Author's response: We appreciate the reviewer's comment and suggestion. We have revised our discussion section to integrate the reviewer's suggestion as follows (please refer to lines 339 to 346; pages 20-21 in the manuscript):

“Based on our study's findings, we recommend the development of specialized interventions to improve road safety for elderly cyclists. Our analysis reveals that older cyclists are at a higher risk of being involved in overtaking crashes, with this increased risk being strongly linked to declines in cognitive capabilities associated with aging. To address this issue, we advocate for the implementation of targeted cognitive training programs specifically designed for elderly cyclists. These programs should focus on enhancing critical skills such as reaction time, situational awareness, and decision-making abilities, which are crucial for reducing crash risk and improving overall road safety. “

4.5.7 Now this is a good statement that should have followed your first sentence, starting from the full stop after segments. then you can now show us how similar it is with what Pai and others found.

Author's response: We appreciate this reviewer's comment. If we understand this reviewer correctly, this reviewer makes a valid argument that Advanced Stop Lines (ASLs), also called bike boxes that had been implemented in the UK for decades, would be beneficial in reducing conflicts between cars and cyclists. However, our study focuses on cyclist crashes that occurred on road segments only (i.e., 20 metres away from junctions); as a result, we remain reserved with discussing this finding with this engineering measure (i.e., ASLs).

In addition to this, we routinely discussed our current findings with those of Pai; for instance, HGVs, unlit streets and midnight hours, and taxis have been similarly identified as a risk factor for overtaking crashes, rear-end crashes, and door crashes, respectively.

4.6 discussions.

4.6.1 They need to tell us how they tried to minimize the biases that could have been introduced by the many study limitations identified for this study.

Author's response: We appreciate this reviewer's comment. One inherent problem with police-reported crash data is the variables not readily available, hereby causing unobserved heterogeneity across the observations. To overcome such a limitation, we estimated separate regression models, as suggested by Kim et al. (2006), for the three crash types; such an approach provides greater explanatory power compared to single overall models. Further, we conducted joint-effect analyses of several variables of interest that capture heterogeneity. In our previous studies, we adopted the above-mentioned approaches to overcome the inherent problem with a success (see, for example, Pai and Saleh, 2008; Pai and Jou, 2014).

To clarify this, the following statements have been added to the Discussion section of the manuscript (please refer to lines 391 to 397; page 23 in the manuscript):

“One inherent problem with police-reported crash data is the variables not readily available, hereby causing unobserved heterogeneity across the observations. To overcome such a limitation, we estimated separate regression models, as suggested by Kim et al. (e.g., d), for the three crash types; such an approach provides greater explanatory power compared to single overall models. Further, we conducted joint-effect analyses of several variables of interest that capture heterogeneity. In our previous studies, we adopted the above-mentioned approaches to overcome the inherent problem with a success (e.g., e, f).”

d: Kim, D., Washington, S., Oh, J., 2006. Modelling crash outcomes: new insights into the effects of covariates on crashes at rural intersections. *Journal of Transportation Engineering*. 132 (4), 282-292.

e: Pai CW, Jou RC, 2014. Cyclists' red-light running behaviours: An examination of risk-taking, opportunistic, and law-obeying behaviours. *Accident Analysis and Prevention*. 62,191-198.

f: Pai CW, Saleh W., 2008. Modelling motorcyclist injury severity by various crash types at T-junctions in the UK. *Safety Science*. 13, 98-98.

4.6.2 Present both the strength and limitations of the study. And you have really brought the limitation well, but my question would be, despite knowing all these why did you decided to carry on to utilised this dataset as opposed to others. Please tell us how you catered for these limitations as away of reducing bias that might have been introduced by them

Author's response: We appreciate this reviewer's comment. We have added a section discussing the strengths of our study before addressing its limitations as follows (please refer to lines 370 to 377; page 22 in the manuscript):

“The strengths of this study include the use of STATS19 datasets spanning from 1991 to 2020, which provides a robust statistical foundation and a broad perspective on trends in bicycle crashes. By focusing specifically on three crash types on road segments—overtaking, rear-end, and door crashes—the study provides a comprehensive and focused analysis, which can yield more actionable insights and more effective recommendations. The UK-based dataset ensures that the findings are particularly relevant for local policy and safety interventions. Additionally, the application of statistical techniques and the consideration of various factors, such as crash partner and time of day, enhance the validity and depth of the analysis.”

Dear Editors and Reviewers,

We greatly appreciate the valuable comments and suggestions raised by reviewers. Please very kindly see our responses below, as well as the revised manuscript. We would be glad if you could have our manuscript reviewed again.

Best regards,

Chih-Wei Pai (Prof)

Graduate Institute of Injury Prevention and Control College of Public Health

Taipei Medical University

Reviewer 2:

1.1 In the Abstract as well as in the results (main text) AOR sometimes expressed with three digits (decimals) and other places two decimals (please consider and use effective digits “decimals”).

Author’s response: We appreciate the reviewer’s comment and suggestions. All AORs have been amended to two decimals (Please refer to lines 34 to 40 on page 2 in the manuscript).

1.2 In the abstract “results section”: the AOR are sometimes very narrow (please explain).

Author’s response: We appreciate the reviewer’s comment and question. The narrow confidence intervals (CIs) for the adjusted odds ratios (AORs) indicate high precision in our estimates. This precision is primarily due to our large sample size, which reduces variability and enhances reliability. For example, the AOR for “male as crash partner” in overtaking crashes is 1.28 with a CI of 1.25-1.33, reflecting a strong effect size and contributing to the narrow CI. Variability and heterogeneity in the data can affect CI width. Risk factors with more consistent effects across the dataset often show narrower CIs (e.g., a).

a. Katz, M. H. (2011). *Multivariable Analysis: A Practical Guide for Clinicians and Public Health Researchers*.

1.3 In the introduction: word roundabouts are repeated “study demonstrated that roundabout significantly reduces -----“

Author’s response: We appreciate the reviewer’s comment and suggestions. We have revised the manuscript. (Please refer to lines 74 to 76; page 4 in the manuscript):

“One study found that roundabouts with dedicated cycle tracks significantly lower the risk of injury for cyclists compared to those without such bicycle infrastructure.”

1.4 In the rationale, the authors still need to emphasize the significance of the three types of crashes, this part of the introduction barely touched this point????

Author’s response: We appreciate the reviewer’s comment and suggestions. We have revised the manuscript. (Please refer to lines 104 to 110; pages 5 -6 in the manuscript):

“The high mortality rate from crashes on road segments underscores the significant risks linked to overtaking, rear-end, and door crashes. Overtaking, involving high-speed maneuvers, greatly increases the likelihood of severe accidents. Rear-end crashes, frequently triggered by sudden stops or aggressive tailgating, pose a persistent threat to cyclists. Furthermore, injuries sustained by cyclists striking an opening car door can be devastating due to the impacts from the door, ground, or vehicles behind. These critical issues highlight the urgent need for identifying risk factors for these crashes.”

Statistical analysis:

1.5 - Rationale for considering p value of 0.2 at the univariate (bivariate) level to be incorporated in the multiple Logistic regression models???

Author's response: We appreciate the reviewer's comment and question. In the first and second round of review, this reviewer expressed concerns over our use of Chi-square tests to examine the relationship between three crash types and the independent variables. We have now opted to estimate the crude odds ratio by univariate logistic regressions. Please kindly see Table 4 lines 259 to 260; page 15 in the manuscript.

1.6- How the data were handled statistically: descriptive and inferential methods should be mentioned in this section

Author's response: We appreciate the reviewer's comment and question. In response to your comment, we have revised the section on statistical handling to provide a more comprehensive explanation of both the descriptive and inferential methods employed. (Please refer to lines 182 to 191; page 9 in the manuscript).

"We initially utilized descriptive statistics to examine the distribution of crash types across various variables such as lighting conditions, speed limit, time of day, and day of the week. Demographic details concerning cyclist casualties encompassed age and sex, while information about the crash partner included vehicle type, age, and sex. This preliminary analysis provided a general picture of basic characteristics of the data and identification of potential patterns. For inferential analysis, we applied the Chi-squared test to investigate associations between crash type and various factors, including cyclist and motorist characteristics, vehicle features, roadway conditions, and temporal variables. We then estimated crude odds ratios by estimating univariate logistic regression and adjusted odds ratios by multivariate logistic models, respectively."

1.8- What type of model was used (stepwise, or else), how the model was tested to be fit???

Author's response: We appreciate the reviewer's comment and question. We used multivariate logistic regression with backward selection to compute adjusted odds ratios (AORs). This method involves initially including all potential predictors and then iteratively removing the least significant variables based on their p-values.

In terms of model fit statistics, the final models were chosen based on the ρ^2 statistics (e.g., b). The ρ^2 statistics for the estimated models range from 0.327 to 0.398, indicating a reasonable model fit.

- b. Ben-Akiva, M. E., & Lerman, S. R. (1985). *Discrete choice analysis: theory and application to travel demand* (Vol. 9). MIT press.

1.9- How the variables were categorized to be suitable for the inclusion of logistic regression analysis?

Author's response: We appreciate the reviewer's comment and question. Considering findings from past studies and selecting the model with the most parsimonious and robust statistical properties (e.g., goodness of fit, reasonable parameter magnitudes, and t-statistics), the variables were categorized and explained as follows:

First, age data were divided into four categories: ≤18 (not of legal driving age), 19–40, 41–64, and ≥65 (defined as older age by WHO standards). This classification highlights the different risk profiles associated with each age group.

The variable "time of crash" was classified into four periods—midnight (00:00–06:00), rush hours (07:00–08:00 and 17:00–18:00), non-rush hours (09:00–16:00), and evening (19:00–23:00)—to account for fluctuations in traffic patterns and accident likelihood throughout the day.

Speed limits were categorized by location into two types: nonbuilt-up areas (rural, ≥40 mph) and built-up areas (urban, 20–30 mph).

Day of the week was grouped as either weekday or weekend to evaluate variations in crash patterns.

These classifications have been commonly adopted in safety literature (e.g., c; d).

- c. Widodo, Akhmad Fajri, et al. "Walking against traffic and pedestrian injuries in the United Kingdom: new insights." *BMC public health* 23.1 (2023): 2205.
- d. Wiratama, Bayu Satria, et al. "Joint effect of heavy vehicles and diminished light conditions on paediatric pedestrian injuries in backover crashes: a UK population-based study." *International journal of environmental research and public health* 19.18 (2022): 11689.

110- The reference group in the multivariate regression table is not consistent along the three types of crashes??? Please explain.

Author's response: We appreciate the reviewer's comment and question. The reference groups in the univariate and multivariate analysis have been assigned consistent. Please kindly see Table 4 lines 259 to 260; pages 14-15 and Table 5 lines 292 to 293; pages 16-17 in the manuscript.

1.11- Joint sensitivity analysis should be mentioned in this section "indication, methods and output"

Author's response: We appreciate the reviewer's insightful comments and suggestions. To illustrate the effectiveness of models with joint effects, we found that these models produced a

higher log-likelihood at convergence and demonstrated an improved overall fit, as indicated by a better ρ^2 statistic.

Moreover, we performed a likelihood ratio test (e.g., e) to confirm the superiority of the joint effects models over the general models. The test statistic is given by:

$$\chi^2 = -2[LL(\beta_G) - LL(\beta_J)]$$

Where $LL(\beta_G)$ represents the log-likelihood at convergence for the general model, and $LL(\beta_J)$ is for the joint effects model. This statistic follows a χ^2 distribution, with degrees of freedom equal to the difference in the number of parameters between the general and joint effects models.

- e. Vuong, Q.H., 1989. Likelihood ratio tests for model selection and non-nested hypothesis. *Econometrica* 57, 307-333.

Results:

1.12- The previous comments on using the Chi-square test remained the same??? Non-specific, non-parametric test and can't point out to the direction of significance???

Author's response: We appreciate this reviewer's comment. In addition to the multivariate logistic regression, we have now estimated the univariate logistic regression models. Please kindly see Table 4 lines 259 to 260; pages 14-15 and Table 5 lines 292 to 293; pages 16-17 in the manuscript.

1.13- What software used to produce figure 2???

Author's response: We appreciate the reviewer's comment and question. We recreated the figure from the previous article (e.g., f) using Photoshop and then edited it in PowerPoint.

- f. Pai C-W. Overtaking, rear-end, and door crashes involving bicycles: an empirical investigation. *Accid Anal Prev.* 2011;43(3):1228-35.

Review 4

4.1 This has been addressed but in the main document start with background under the background sentences, conclude it with the objective, instead of presenting it as a separate paragraph.

Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (please refer to lines 23 to 27 ; page 2 in the manuscript):

"**Background and Objective:** Relevant research has provided valuable insights into risk factors for bicycle crashes at intersections. However, few studies have focused explicitly on three common types of bicycle crashes on road segments: overtaking, rear-end, and door crashes. This study aims to identify risk factors for overtaking, rear-end, and door crashes that occur on road segments."

4.2 I understand this response; however, you need to conduct a normality check for all continuous variables like age and others like distance. This helps you to present either the mean age or the median age

Author's response: We appreciate the reviewer's comment and suggestions. Normality check for continuous variables is needed only while estimating a linear regression model. In our study, we estimated several logistic models in which testing for normality and homoscedasticity is not needed. For a comprehensive discussion on the derivation of logistic regression models, see Hosmer et al. (e.g., g).

g. Hosmer Jr, David W., Stanley Lemeshow, and Rodney X. Sturdivant. Applied logistic regression. John Wiley & Sons, 2013.

4.3 N(%) consider using this type of reforestation and removed the percentage signs from the table

Author's response: We appreciate the reviewer's comment and suggestions. We have removed the percentage signs and replaced them with "n (%)" in the tables 1, 2 and 3. (Please refer to lines 221-222 of page 11; lines 237 -238 of pages 12- 13; lines 254-255 of pages 13- 14 in the manuscript).

4.4 Data analysed should replace this, you didn't collect data

Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (Please refer to lines 160; page 8 in the manuscript):

"Data analysis"

4.5 I insist this be removed, but keep the proportion there and take this up and say N(%) or read other publication to see how this is presented

Author's response: We appreciate the reviewer's comment and suggestions. We have removed the percentage signs and replaced them with "n (%)" in the table1, 2 and 3. Please refer to lines 221-222 of page 11; lines 237 -238 of pages 12- 13; lines 254-255 of pages 13- 14 in the manuscript.

4.6 This has not been fully addressed. What the authors did was just introduced the corresponding Odds Ratios and P-Values but no result interpretation. Consider doing something like this, "having a HGVs as crash partners had 2.9 times higher likelihood of being involved in overtaking crash", something like this for all the significant variables.

Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (Please refer to 293 to 295; page 17 in the manuscript):

"In overtaking crashes, the presence of heavy goods vehicles (HGVs) as partners increases the likelihood by 1.3 times (AOR = 1.30, 95% CI = 1.27-1.33; p < 0.001)."

4.7 This has now been introduced, however, start with what you found, then bring the reason supporting those findings and lastly place it in the context of other study and cite it.

Author's response: We appreciate the reviewer's comment and suggestions. We have outlined the reasons supporting these findings and, finally, situated them within the context of existing research, providing appropriate citations. (Please refer to lines 344 to 347; pages 19-20 in the manuscript):

"Their large blind spots make it difficult for drivers to see cyclists, increasing the likelihood of crashes during overtaking [e.g., c]. Additionally, HGVs are less manoeuvrable compared to passenger cars, which reduces their ability to avoid crashes if cyclists suddenly enter their path [e.g., d]. The speed and distance perception issues between HGVs and cyclists further complicate the judgment of safe overtaking gaps[e.g., e]."

c. Marshall, Russell, and Stephen Summerskill. "An objective methodology for blind spot analysis of HGVs using a DHM approach." *DS 87-8 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 8: Human Behaviour in Design, Vancouver, Canada, 21-25.08. 2017.* 2017.

d. Frings, Daniel, Andy Rose, and Anne M. Ridley. "Bicyclist fatalities involving heavy goods vehicles: Gender differences in risk perception, behavioral choices, and training." *Traffic injury prevention* 13.5 (2012): 493-498.

e. Chew, Esther Li-Wen, and Amanda Stephens. "Human Factors That Impact HGV Drivers From Being Aware of VRUs Through Direct and Indirect Vision Mechanisms."

4.8 I think you need to reference this in the method section also where you discussed the data source. Some readers don't reach here

Author's response: We appreciate the reviewer's comment and suggestions. We have revised the manuscript. (please refer to 135 to 137; page 7 in the manuscript):

"The data that support the findings of this study are openly available at <https://figshare.com/ndownloader/files/48173452>."