Transport Reviews

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ttrv20

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To cite this article: Roni Utriainen, Steve O’Hern & Markus Pöllänen (2022): Review on single-bicycle crashes in the recent scientific literature, Transport Reviews, DOI: 10.1080/01441647.2022.2055674

To link to this article: https://doi.org/10.1080/01441647.2022.2055674

Published online: 28 Mar 2022.

TRANSPORT REVIEWS
https://doi.org/10.1080/01441647.2022.2055674

RESEARCH ARTICLE

Review on single-bicycle crashes in the recent scientific literature

Roni Utriainen [a], Steve O'Hern [a,b] and Markus Pöllänen [a]

[a]Transport Research Centre Verne, Tampere University, Tampere, Finland; [b]Monash University Accident Research Centre, Monash University, Clayton, Australia

ABSTRACT
Cycling delivers public health benefits and reductions in carbon dioxide emissions compared to motor vehicle travel. However, riding a bicycle has a higher injury rate per kilometres travelled. Therefore, the shift from cars to bicycles has the potential to cause undesired impacts in terms of road safety. Among cycling injuries, single-bicycle crashes (SBCs) constitute a significant number of all injuries, but the size of the problem is somewhat unknown. This study focuses on the data mainly from the 2010s based on the scientific publications, and explores the proportion and the characteristics of SBCs internationally. Altogether 22 relevant studies where found. In the different studies, the share of SBCs among injured cyclists varies considerably from 17% to 85%. When considering studies based on larger samples and more representative data, the share of SBCs varies between 52% and 85%. It is suggested that SBCs are underreported in certain datasets depending on the methodology chosen to analyse SBCs. The proportion of SBCs has not changed notably during the early twenty-first century. The main characteristics related to SBC events are loss of control or skidding in slippery conditions. The interplay between SBC-related factors such as the infrastructure, the cyclist and other road users, and the bicycle should be further investigated to better understand the causes of SBCs.

ARTICLE HISTORY
Received 30 August 2021
Accepted 11 March 2022

KEYWORDS
Single-bicycle crash; safety; cycling; bicycling; biking; road safety

1. Introduction

Public health benefits and the reduction of carbon dioxide (CO_2) emissions are important arguments to promote cycling instead of travel using private motor vehicles (Deenihan & Caulfield, 2014). However, the paradigm shift has the potential to cause undesired impacts in terms of road safety. People experience higher rates of fatal injury and non-fatal injury per kilometre travelled and per trip when riding a bicycle compared to when travelling via car (Bjørnskau, 2015; Garrard, Greaves, & Ellison, 2010; Pucher & Dijkstra, 2003). Even if it has been indicated that more cycling lowers the risk of injury, the absolute number of injured cyclists may increase when cycling mode share increases (Elvik & Goel, 2019).

CONTACT Roni Utriainen roni.utriainen@tuni.fi Transport Research Centre Verne, Tampere University, Tampere, Finland

Globally vulnerable road users, such as cyclists, pedestrians, and motorcyclists, are involved in more than half of all road trauma (WHO, 2018). In Europe, cyclists represent approximately eight percent of fatally injured road users, compared to 47% of cases which involve passenger car occupants (ERSO, 2018). However, recent research comparing serious injuries in northern European countries found that the share of serious cyclist injuries is similar with passenger car occupants in Sweden and Finland and are higher in the Netherlands (Utriainen, Pöllänen, & Liimatainen, 2018). These statistics align with road safety research from the Netherlands which found that cyclists represent approximately 60% of serious injuries (Weijermars, Bos, & Stipdonk, 2016). Highlighting the importance of investigating serious injuries statistics to increase our understanding of cycling safety, particularly as cycling mode share increases in various cities throughout the world (ITF, 2020).

Multiple studies, from various jurisdictions, have found single-bicycle crashes (SBCs), in which other road users are not collided with, to be a frequent crash type among injured cyclists (Beck et al., 2019; Ohlin, Algurén, & Lie, 2019). SBCs also play a role in bicycling fatalities (Boufous & Olivier, 2016; O'Hern & Oxley, 2018; Schepers, Stipdonk, Methorst, & Olivier, 2017). Furthermore, time trend analysis indicates that the number of fatalities due to SBCs has been on the rise in Australia and the Netherlands despite an overall reduction in the number of cyclist fatalities (Boufous & Olivier, 2016; Schepers et al., 2017), which may indicate the changing risk profile for cyclists as dedicated infrastructure such as separated facilities are increasingly introduced (Boufous & Olivier, 2016). SBCs have been identified as a common crash type for cyclists since at least the 1980s (Björnstig & Näslund, 1984; Jacobson, Blizzard, & Dwyer, 1998), but they have received a lot of attention in recent years (see e.g. Gildea, Hall, & Simms, 2021; Olesen, Madsen, Hels, Hosseinpour, & Lahrman, 2021).

The role of SBCs is also particularly significant in non-fatal crashes (Schepers et al., 2015). Meta-analysis conducted by Schepers et al. (2015) reviewing SBC research up to 2013 found that 60–95 percent of injuries when riding a bicycle result from SBCs, highlighting the magnitude of the problem. SBCs typically result in less severe injuries compared to crashes between cyclists and motor vehicles (Cripton et al., 2015; Ohlin et al., 2019), but the large proportion of SBCs makes these crashes problematic from a traffic safety point of view. Furthermore, throughout the early twenty-first century, the number of cycling trips has increased in many large cities (ITF, 2020), which makes it necessary to update the current understanding on bicycle crashes and SBCs in particular.

Official road safety statistics, which represent high coverage in terms of fatal crashes are often based on police data. However, these datasets have been found to present biased information on the magnitude of SBCs (Boufous, de Rome, Senserrick, & Ivers, 2013), due to underreporting to police. Researchers suggest that SBCs should rather be explored by looking at casualties treated in hospital or at emergency departments (Myhrmann, Janstrup, Møller, & Mabit, 2021). However, while a more reliable number of injured cyclists is typically reported in hospital and emergency department records, there are also noted limitations in these data sources as they do not capture all crashes either, particularly crashes resulting in low severity injuries (O'Hern & Oxley, 2019). Furthermore, unlike police data, hospital records often do not include information on crash characteristics, which are necessary for proactive road safety work and to better understand underlying crash risk factors. This emphasises the importance of complimentary data sources alongside police data (Schepers et al., 2015).

To our knowledge, recent academic studies do not provide a literature review on the characteristics of SBCs or other factors describing the crash event. Several studies focusing on SBCs in certain countries (e.g. Hertach, Uhr, Niemann, & Cavegn, 2018; Utriainen, 2020) or in specific regions inside a country (e.g. Boufous et al., 2013) were identified. However, the number of injured cyclists included in a single study is often small, which limits the ability to draw wider conclusions. Therefore, a literature review including information on a larger cohort of injured cyclists internationally, supports updating and building a more comprehensive understanding of SBCs. Hence, this study aims to explore the characteristics of SBCs and their crash-related factors by reviewing academic literature. In addition, the study aims to update the current knowledge on the proportion of SBCs among injured cyclists to assess the magnitude of the problem. The focus is on studies that report crash data mainly from the 2010s to identify the most recent information. Comparison is made to the literature review by Schepers et al. (2015) in which the proportion of SBCs was reported based on the research up to 2013. This study aims to address the following research questions:

- What has been the proportion of SBCs among injured cyclists in different countries when looking at the crash data mainly from the 2010s?
- How has the proportion of SBCs changed in the twenty-first century?
- What are the main characteristics of SBC events?

2. Methods

A literature search of scientific and peer-reviewed articles was undertaken in Scopus, ScienceDirect, PubMed, Google Scholar, TRID, PsycINFO, EMBASE and CINAHL databases in November 2021 (Figure 1).

The main area of interest is in the SBCs which have occurred in the 2010s hence the search was restricted to scientific articles published between January 2010 and November 2021. It is noted that there is often a delay between when studies are published and when the analysed crashes have occurred, as such studies from the early 2010s often include data prior to 2010. These manuscripts were retained in the sample, however, studies that focused predominantly on crashes before 2010 were omitted in the second phase of the literature review.

The search was made by using the logical search term "single-bicycle crash*" OR "single bicycle crash*" OR "single-bicycle accident*" OR "single bicycle accident*" OR "single-bicycle incident*" OR "single bicycle incident*" OR "single cycling crash*" OR "single-cycling crash*" OR "single-cyclist crash*" OR "single cyclist crash*" OR "single cyclist-only event*" OR "single-bicycle only crash*" OR "non-motor vehicle crash*" OR "non-motor vehicle crash*" OR "single-bicycle collision*", which refer to bicycle crashes, in which the cyclist fell or collided with a fixed object, and crashes that did not involve a collision between a cyclist and another road user. It should be noted that in Google Scholar search the asterisk (*) is not recognised so the search is only for exact terms. In total, 174 unique articles were identified that included at least one of the search terms. The selection of the literature included the following two phases:

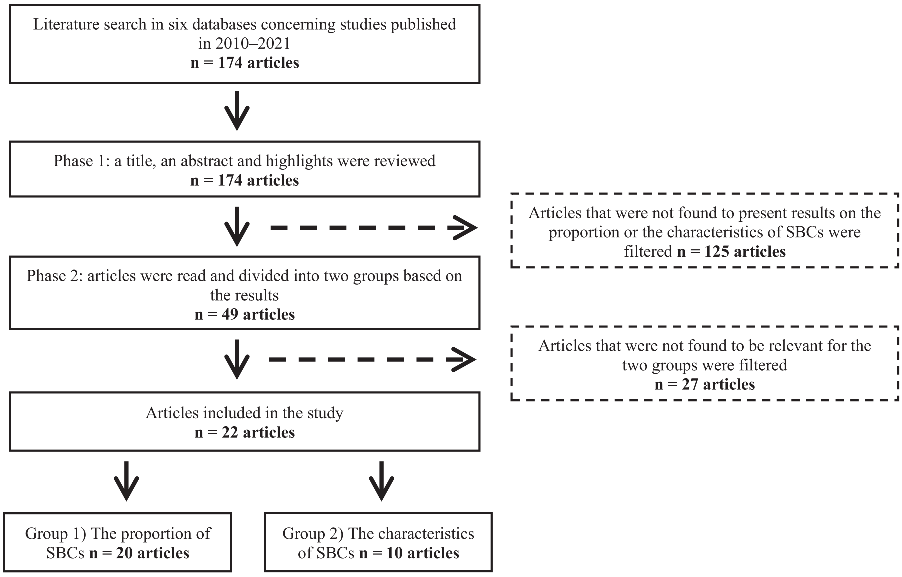

Figure 1. The phases of the literature review.

- Phase 1: Title, abstract and highlights (if available) were reviewed by one researcher for each article (*n* = 174). SBCs were judged to be a part of the article's focus area, if SBCs or other relevant terms referring to SBCs were mentioned in the title, abstract or highlights, or if the text otherwise indicated that the article may contain information about SBCs, i.e. different crash types or characteristics of bicycle crashes were mentioned. An article was moved to Phase 2, if the study at least partly focused on SBCs. The Phase 1 review excluded 125 articles, leaving 49 possibly relevant articles for full review in Phase 2.
- Phase 2: Articles were examined in more detail to find information on SBCs. Articles that do not report relevant research results on SBCs were excluded. In addition, articles that mostly reported crashes that occurred before 2010 were excluded. Twenty-two (22) manuscripts were retained in this stage of the study. These articles were further divided into two groups according to the SBC-related findings presented in the articles. The groups are (1) articles that reported on the proportion of SBCs (*n* = 20) and (2) articles that reported on the characteristics of SBCs (i.e. factors describing the occurrence of the crash) (*n* = 10). Eight studies were placed into both groups. Discussion of the manuscripts in these two groups is the basis of section 3.

Once the relevant articles were identified, results on the number of SBCs and all injured cyclists in each study in Group 1 were identified to determine the proportion of SBCs. The range and the mean of the proportions with 95% confidence intervals were calculated based on the data reported in the studies. Studies were classified into two groups based on their study design. The two groups represented those that are potentially underestimating the share of SBCs (i.e. studies with relatively small sample size or studies that are based on surveys or insurance data), and studies based on hospital data and with larger sample size. As mentioned in Introduction the latter is considered a more reliable estimate on the proportion of SBCs. To identify possible changes in the proportion of SBCs between the 2010s and early 2000s, the results are compared to the findings of previous literature review on SBCs done by Schepers et al. (2015).

Furthermore, the association between the proportion of SBCs and the mode share of cycling were analysed in different countries for studies in Group 1. Countries with more than 1,000 analysed SBCs were included in the analysis. When more than one study in a country was available, the proportion of SBCs is based on the sum of analysed crashes. The mode share of cycling in each country is based on the distribution of trips in different countries. The mode shares were determined by searching national travel surveys or transport-related policy documents. The results are presented to illustrate the variation between mode share of cycling and the share of SBCs by country.

For studies in Group 2, the three most frequent characteristics of SBCs in each study is presented. In addition, the crash characteristics are presented using a Safe System framework (European Commission, 2020), i.e. factors related to infrastructure, bicycle, road users, and speed are discussed. Table 1 presents the variables analysed for each study group, based on the available data in the respective manuscripts.

3. Results and discussion

Results and discussion are presented together based on the two groups that are depicted in section 2 (Figure 1). Research related to the proportion of SBCs (group 1) is described in section 3.1 and research related to the characteristics of SBCs in section 3.2 (group 2). Each section provides a summary of the included studies and synthesis of findings. The overall discussion is presented in section 3.3 and conclusions in section 4.

3.1. Research regarding the proportion of single-bicycle crashes

3.1.1. Literature on the proportion of SBCs

In total, 20 articles were identified reporting the proportion of SBCs, of which 12 articles analysed the data of more than 500 injured cyclists (Table 2). Articles reported crash data mostly from the 2010s, albeit some studies included data from the late 2000s. Articles focusing on SBCs were mostly from Europe, representing 15 of the 20 publications. Sweden, the Netherlands, and Denmark were well represented, each with three studies, with the largest number of studies coming from Australia (*n* = 4).

Table 1. Variables reported for each study in Group 1 (articles on the proportion of SBCs) and 2 (articles on the characteristics of SBCs).

	Group 1 (the proportion of SBCs)	Group 2 (the characteristics of SBCs)
Variables	• Study country • Study period • The general aim of study • Data source • Study design • Is the term "single-bicycle crash" in use? • Share of SBCs • Number of SBC victims • Number of all injured cyclists	• Study country • Study period • Number of SBC victims • Three most common crash types or related factors of SBCs with the share of the factor in SBCs

Table 2. Studies that have reported the number of injuries that resulted from SBCs.

Study country and period	Authors	The aim of study is related to	Data source	Study design	Is the term "single-bicycle crash" in use?	Share of SBCs	Number of SBC victims	Number of all injured cyclists
The Netherlands, 2012	Scholten et al. (2015)	Incidence and costs of bicycle crashes (BCs)	1	Retrospective	Yes	68%	51,100[bc]	74,752
Sweden, 2013–2017	Ohlin et al., (2019)	Characteristics of BCs	1	Cross-sectional	Yes	79%	34,461	43,594
Sweden, 2006–2016	Axelsson and Stigson, (2019)	Characteristics of BCs and impact of bicycle helmets	1	Retrospective cohort[a]	Yes	82%	20,200[b]	24,623 (people aged 0-17)
Finland, 2016–2017	Utriainen (2020)	Characteristics of BCs	3	Cross-sectional[a]	Yes	72%[d]	6,651[d]	9,268
Sweden, 2010	Kjeldgård et al. (2019)	Characteristics of BCs	1	Register study	Yes	85%	6,484	7,643
Denmark, 2010–2015	Møller et al. (2021)	Characteristics of BCs and the added value of bicycle crash descriptions	1	Register study	Yes	54%	2,287	4,205
Denmark, 2010–2015	Myhrmann et al. (2021)	Characteristics of BCs	1	Cross-sectional[a]	Yes	52%	1,726	3,331
Switzerland NA–2016	Hertach et al. (2018)	Characteristics of BCs	2	Cross-sectional[a]	No, single-vehicle crash	17%	638	3,658 (electrically assisted bicycle riders)
The Netherlands, 2011–2013	Schepers, Fishman, Den Hertog, Wolt, and Schwab, (2014)	Likelihood and characteristics of BCs	1	Case-control	Yes	68%	1,351[c]	1,993
Norway, 2005–2016	Næss et al. (2020)	Trends in BCs	1	Retrospective	Yes	68%	1,053	1,543
Ireland, 2013–2018	Gildea and Simms (2021)	Characteristics of BCs	2	Retrospective cohort[a]	No, single cyclist collision	29%	291	1,018
Denmark, 2012–2013	Hosseinpour et al. (2021)	Characteristics of BCs	2	Retrospective cohort[a]	Yes	50%	349	693
Canada, 2005–2019	Fischer, Nelson, Laberee, and Winters, (2020)	Characteristics of BCs	2	Cross-sectional[a]	Yes	25%	70	281
Australia, 2009–2010	De Rome et al. (2014)	Characteristics of BCs	1, 2	Cross-sectional	No, single bicycle-only crash	60%	122	202
Australia, 2013	Beck et al. (2016)	Characteristics of BCs	1, 2	Prospective	No, single cyclist-only event	56%	105	186
Finland, 2009–2018	Airaksinen, Handolin, and Heinänen (2020)	Characteristics of road traffic crashes	1	Retrospective cohort[a]	No, single cycling accident or crash	35%	64	183
Belgium, 2013–2015	Vanparijs, Panis, Meeusen, and de Geus (2016)	Characteristics of BCs	2, 3	Retrospective	Yes	31%	50	163 (people aged 14-18)

Australia, 2013	Beck et al. (2019)	Characteristics of BCs	1, 2	Prospective	Yes	48%	62	129
Australia, 2014–2017	Meuleners et al. (2020)	Characteristics of BCs	1, 2	Prospective	No, single cyclist crash	39%	39[c]	100
The Netherlands, 2012	Boele-Vos et al. (2017)	Characteristics of BCs	1, 2	Retrospective	Yes	66%	27[c]	41 (people aged 50 and over)

Note: Data source refers to the crash data on injured cyclists that was analysed in the article, where 1 = hospital and/or emergency department data, 2 = survey data or data is based on self-reported crashes and 3 = insurance data.

[a]Study design is defined by the authors of this study, as it is not reported in the study.

[b]The approximate number of SBCs was calculated by multiplying the share of SBCs by the total number of injured cyclists, because the exact number of SBCs was not available.

[c]Subgroups of SBCs are summed up by the authors of this study to give the total number of SBCs.

[d]The figure is based on the average of the lower and upper limits of the range of SBCs, because the exact number of SBCs is not available, but the lower and upper limits are available.

Almost all studies in the group ($n = 19$) focused solely on bicycle crashes and most of them ($n = 16$) analysed the characteristics of crashes or injuries. Retrospective and cross-sectional study designs were the most common. In many cases, study designs were judged by the authors of this study, as they were not reported in many manuscripts. The reported crashes were typically based on emergency department or hospital data ($n = 14$), but surveys or self-reported crashes ($n = 10$) were also typical data sources. Some studies applied the combination of different data sources ($n = 7$). The term "single-bicycle crash" was used in 14 studies and particularly in recently published studies, suggesting that it is becoming the established term to describe bicycle crashes which do not involve another road user as a collision counterpart.

3.1.2. The proportion of SBCs

The results show that the proportion of SBCs among injured cyclists varies between 17% and 85% depending on the study design and reporting country (Table 2). When studies based on other data sources than hospital or emergency department data, or with a sample of less than 500 injured cyclists were excluded, the share of SBC victims varies between 52% and 85%. Suggesting that SBCs are underreported in certain datasets or when using study designs that rely on self-report.

According to the literature review by Schepers et al. (2015) the proportion of SBCs varied between 60% and 95%. However, the highest proportion in their study (95%) was based on one study by Özkan et al. (2012) reporting on only 150 injured cyclists. Excluding the aforementioned study, the largest share of SBCs, reported by Schepers et al. (2015) was 89%, which is closer to the peak of the range in this study. Thus, the range in the proportions of SBCs do not appear to have changed notably in the 2010s compared to previous years. The results show that SBCs are the most common cause of a bicycle crash in most studies. However, there are noticeable differences in the results based on the study jurisdiction and methodology. Studies based on surveys or questionnaires, and other studies with a relatively small sample of injured bicyclists estimate lower proportions of SBCs (17–72%, mean: 53.2%; $n = 12$) compared to studies with a larger sample size and those based on hospital records (52–85%, mean: 72.9%; $n = 8$) (Table 3). Issues regarding reporting of SBCs were previously explored by Boufous et al. (2013), who identified that in police-reported datasets as few as 5% of crashes were SBCs, compared to 55% in hospital data in the state of Victoria, Australia. Møller, Janstrup, and Pilegaard (2021) made similar observations in Aarhus, Denmark. This suggests that the reliability of estimating the proportion of SBCs is largely dependent on the methodology employed in the research and the data source selected.

Table 3 indicates, how the proportion of SBCs varies between the studies. A possible explanation for the large range may be the mode share of cycling in different countries in addition to the type of analysed crash data. The association between the proportion of SBCs and the mode share of cycling is presented in Figure 2. The data from five countries indicates that generally as the mode share of cycling increases so does the proportion of SBCs.

According to the Figure 2, two groups of countries can be identified based on the mode share of cycling. The Netherlands and Denmark create one group. Sweden, Finland, and Norway, where cycling is less popular transport mode compared to the first group, create the other group. The Netherlands and Denmark are known for the

Table 3. Descriptive statistics of studies in Table 2.

Proportion of single-bicycle crashes in injured cyclists	Number of studies	Range of share of SBCs	Mean (95% confidence interval)
Studies based on hospital and/or emergency department data and with more than 500 injured cyclists	8	52%–85%	72.9% (72.5% to 73.3%)
Other studies in Table 2 (i.e. studies based on other data sources or with less than 500 injured cyclists)	12	17%–72%	53.2% (52.1% to 54.3%)
All studies in Table 2	20	17%–85%	71.6% (71.2% to 72.0%)

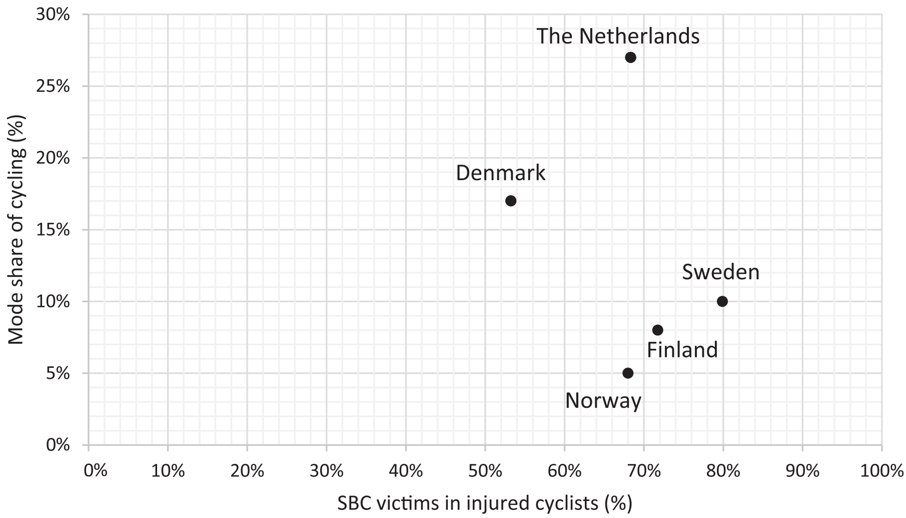

Figure 2. The mode share of cycling and the share of SBC victims in injured cyclists in five countries. The shares of SBCs and the mode shares of cycling are based on the data presented in Appendix A Table A1.

popularity of cycling, which likely indicates better cycling infrastructure and different attitudes towards cycling (i.e. a cycling culture) compared to other countries (Haustein, Koglin, Nielsen, & Svensson, 2020) possibly causing the variance in the analysis.

The relationship between the mode share and the proportion of SBCs indicates that injury crashes between bicyclists and other road users are not relatively as common as SBCs when cycling becomes more common. Hosseinpour, Madsen, Olesen, and Lahrmann (2021) noted that in Denmark, where cycling is a popular transport mode, cycle paths are usually segregated from motor vehicle and pedestrian traffic and hence, cycling at higher speeds may be more attractive compared to other countries, although this may increase the possibility of SBCs with serious injuries. They also argued that the risk of serious injuries in other cycling crashes than in SBCs is lower, because other road users likely have better awareness of cyclists, as cyclists are encountered regularly.

Moreover, one could speculate about SBCs being more common in colder countries (e.g. Sweden, Finland and Norway) than in countries where there is less snow and ice in winter. Because comparable data on SBCs from the sufficiently large number of countries is not available this cannot be confirmed, but studies from the Netherlands indicate that the share of SBCs can be on the same level as in colder countries.

3.2. The characteristics of SBCs

3.2.1. Literature on the characteristics of SBCs

The characteristics of SBCs were analysed for ten articles of which four explored the data of more than 500 injured cyclists (Table 4). The most popular study country was Australia with three studies. All other studies were from Europe. In most studies ($n = 8$), the crash data is based on surveys or self-reporting, but five of these studies combined hospital and/or emergency department data into the dataset. Hospital data is considered the most reliable data source to estimate the number of SBCs as addressed in section 3.1, but this data typically lacks crash characteristics which limits possibilities for detailed analysis. Studies included in Group 2 related to the characteristics of SBCs include eight of the same studies as Group 1 and two new studies.

First, the most common crash types of SBCs are presented in Table 4. Second, the characteristics and contributory factors of SBCs are addressed using a Safe System framework, i.e. factors related to infrastructure, bicycle, and road users and speed are examined individually based on the literature.

3.2.2 The characteristics of SBCs

Loss of control or skidding on a slippery road surface were the most frequent crash-related factors in almost every study (Table 4). In Sweden and Finland, in which icy and snowy conditions are typical in wintertime, skidding due to slippery conditions was recognised in 32–47% of the cases (Ohlin et al., 2019; Utriainen, 2020). Skidding in slippery conditions (e.g. wet or icy road surface) were also the most frequent cases in Switzerland and Ireland (Gildea et al., 2021; Hertach et al., 2018), which indicates that the longer periods of icy and snowy conditions in Northern countries cannot be considered the only cause for the high proportion of slips. Each study from Australia (Beck et al., 2019; De Rome et al., 2014; Meuleners et al., 2020) indicated that the loss of control was the most common type of SBCs, but in these studies the role of slippery conditions is not specified, or its effect is estimated to be minimal. Colliding with an object (e.g. a kerbstone), avoidance of other road users (e.g. a motor vehicle) and an interaction with tram tracks were also identified as typical crash-related factors.

3.2.3. Infrastructure-related factors for SBCs

The infrastructure-related contributory factors for SBCs including road design and maintenance were commonly identified. Icy and snowy road surfaces affected a large share of SBCs (e.g. Ohlin et al., 2019; Olesen et al., 2021) highlighting the need for proper winter maintenance including plowing and deicing. According to Utriainen (2020), the infrastructure-related factors are associated to the season, because these were identified as a contributory factor in 81% of SBCs in winter, but the share was 44% during other seasons when factors related to cyclists, bicycles and an interaction with others were more common compared to winter. Cycling volumes are the lowest in winter in Finland, but the risk of a SBC was estimated to be the highest in winter (Utriainen, 2020). Myhrmann et al. (2021) made an interesting observation on the association between injury severity in SBCs and the road maintenance, as they argued that poor road maintenance has been found to result in less severe injuries, which may be due to more cautious behaviour on poorly maintained sections. Myhrmann et al. (2021) also added that SBCs on well-

Table 4. Studies that have examined the characteristics or crash types of SBCs.

Study country and period	Authors	Data source	Number of SBC victims	Three most common crash types or related factors of SBCs (share of the factor in SBCs)		
Finland, 2016–2017	Utriainen (2020)	3	3,448	Skidding due to a slippery road surface, e.g. ice or snow (47%)	Avoidance of other road users (14%)	Colliding with an object, e.g. a bollard or a kerb (9%)[b]
Denmark, 2010–2015	Myhrmann et al. (2021)	1	1,720	Road-related, e.g. slippery road surface or potholes in the road (39%)	Cyclist-related, e.g. inattention by the cyclist (29%)	Unknown, e.g. specific factor was not identified (25%)
Sweden, 2013–2017	Ohlin et al. (2019)	1, 2	644[a]	Skidding on e.g. ice or snow (32%)[b]	Collision with stationary or temporary object, e.g. a curbstone (18%)[b]	Loss of control during braking or evasive maneuver (13%)[b]
Switzerland, NA–2016	Hertach et al. (2018)	2	638	Skidding on e.g. wet leaves or ice (31%)	Crossing a threshold or collision with an obstacle, e.g. a kerb or pothole (27%)[b]	Getting into or skidding on a tram or railway track (13%)
Denmark, 2012–2013	Olesen et al. (2021)	2	349	Snow or ice as a contributory factor (48%)	A curve or when turning as a contributory factor (22%)	A kerb as a contributory factor (13%)
Ireland, 2014–2018	Gildea et al. (2021)	2	271	Collisions involving slippery roads, e.g. wet or icy. (31%)	Collision involving tram tracks, e.g. a bicycle wheel becoming lodged in tracks (23%)	Collisions involving a kerb (21%)
Australia, 2009–2010	De Rome et al. (2014)	1, 2	122	Loss of control on a straight section (49%)	Colliding with an object (20%)	Loss of control on a curve (13%)
Australia, 2013	Beck et al. (2019)	1, 2	62	Loss of control e.g. in slippery conditions (23%)[b]	Interaction with tram tracks, e.g. turning right across tracks (19%)[b]	Sudden braking to avoid other road users (15%)
Australia, 2014–2017	Meuleners et al. (2020)	1, 2	39	Loss of control (54%)	Colliding with a stationary object (46%)	(No other categories)
The Netherlands, 2012	Boele-Vos et al. (2017)	1, 2	27	Colliding with an object (52%)	Fall from a bicycle (48%)	(No other categories)

Note: Data source refers to the crash data on injured cyclists that was analysed in the article, where 1 = hospital and/or emergency department data, 2 = survey data or data is based on self-reported crashes and 3 = insurance data.
[a]The approximate number of SBCs was calculated by multiplying the share of SBCs by the total number of injured cyclists, because the exact number of SBCs was not available.
[b]The proportion of a SBC-related factor is based on the sum of different factors reported in the literature. The authors of this study made a summation.

maintained roadways are more likely to be severe injuries compared to crashes on well-maintained bicycle lanes, and severe injuries are more likely on road sections next to a poorly maintained bicycle lane, because cyclists may be willing to cycle on a roadway instead of the poorly maintained bicycle lane.

Road design is another important factor, as SBCs were also typically related to the kerbstones, e.g. when the cyclist crosses or leaves the road and hits a kerb. Similarly, crossing tram tracks or cycling next to the tracks were identified as events potentially leading to

SBCs. Proper kerb design (e.g. lowering the kerb at intersections), segregated cycle paths in areas with tram tracks, and sufficiently large approach angles when crossing the tracks are needed (Gildea et al., 2021; Meuleners et al., 2020).

3.2.4. Bicycle-related factors for SBCs

Factors related to the bicycle were not the most common contributory factors, but bicycle-related factors that contributed to the occurrence of SBCs were identified in several studies (e.g. Boele-Vos et al., 2017; Ohlin et al., 2019; Utriainen, 2020). Bicycle-related issues leading to SBCs include for example, hard braking events when the cyclist fell over the handlebar or lost control, or events when the cyclist fell during (dis)-mounting or in slow speed. Adding anti-lock braking systems, in particular to electrically assisted bicycles as well as the solutions to restrict the maximum force of the front brake have been proposed as potential measures to prevent bicycle-related SBCs based on the analysis of crash characteristics (Hertach et al., 2018; Utriainen, 2020). Overall, improved braking stability is an important measure to prevent loss of control due to wheel locking, while studded tyres in winter can also reduce the chance of skidding (Rizzi, Rizzi, Kullgren, & Algurén, 2020). Better stability of the bicycle and setting the technical characteristics of the bicycle (e.g. saddle height) according to the user is needed to prevent SBCs due to (dis)mounting (Boele-Vos et al., 2017; Ohlin et al., 2019).

3.2.5. Factors related to road users and speed for SBCs

The role of the road user, the cyclist in this case, is also emphasised in preventing SBCs. The quality of the cycling facilities including proper winter maintenance is an important part of preventing SBCs (Schepers, de Geus, van Cauwenberg, Ampe, & Engbers, 2020), but cyclists should also anticipate potentially slippery sections (e.g. curves) and decelerate to avoid losing control (Beck et al., 2019). For instance, riding too fast for the situation was recognised as a typical event prior to the SBC among riders of electrically assisted bicycles (Hertach et al., 2018).

Myhrmann et al. (2021) found that SBCs on low volume roads tend to cause more serious injuries, which, they suggest, may be due to riskier behaviour and higher speeds of the cyclists compared to high volume roads with less space. Other conditions where safe cycling behaviour should be especially considered are dark conditions and nighttime, because these conditions also seem to increase the risk of serious injury in SBCs (Hosseinpour et al., 2021; Myhrmann et al., 2021). In addition to the attitudes towards safe cycling, bicycle handling skills are another point of view that should be considered. De Rome et al. (2014) suggest that safety improvement strategies should consider necessary skills to handle and ride a bicycle, but the credible enforcement of speed and cycling under the influence of alcohol should also be required in these strategies. However, as injuries due to SBCs are typically suffered by experienced cyclists with a high riding exposure and several weekly cycling trips (Beck et al., 2019; Hertach et al., 2018), lack of cycling skills is probably not the typical cause of the crash. Instead, cycling under the influence of alcohol seem to be a more common contributory factor in SBCs compared to other types of bicycle crashes (Møller et al., 2021).

Other road users beside the cyclist have their role in crash avoidance that should be looked at when preventing SBCs, as the avoidance of other road users (e.g. a car driver) was also identified as a typical event leading to a SBC (e.g. Beck et al., 2019;

Utriainen, 2020). By investigating the fatal crashes of cyclists when a car driver has been the collision counterpart and the driver had an obligation to yield, it is known that the driver did not typically recognise the cyclist early enough (Utriainen & Pöllänen, 2021), which makes it important that the driver when in potential interaction situation focuses on recognising the cyclist and other road users. It is also important that when required cyclists obey their obligation to yield when encountering the driver, which is not always the case (Räsänen, Koivisto, & Summala, 1999). It should be noted that the avoidance cases can also relate to other cyclists or pedestrians, which is why it is necessary to segregate cyclists and pedestrians in areas with a high bicycle or pedestrian volumes (Finnish Transport Infrastructure Agency, 2020).

3.3. Overall discussion

Encounters with the drivers of motor vehicles have typically been the topic of discussion regarding cyclist safety. Although collisions with motor vehicles usually lead to more serious injuries (e.g. head injuries) than other cycling crashes (Scholten, Polinder, Panneman, Van Beeck, & Haagsma, 2015; Weijermars et al., 2016), the results indicate that injuries to cyclists are most frequently caused by SBCs. A possible explanation for the biased understanding of typical cycling crashes may be that police-reported crashes, which underestimate SBCs, are the basis of crash statistics in many countries. To avoid the view that collisions with motor vehicles would be the most common crash type and to increase cyclists' awareness of the risk of SBCs education campaigns may be necessary to inform cyclists on the most likely bicycle crash scenarios, such as loss of control and skidding, and how to avoid these cases (Billot-Grasset, Amoros, & Hours, 2016).

Processes to aggregate crash statistic data sources should be developed to learn more about the prevalence of SBCs and to better understand factors leading to these crashes (Utriainen, 2020). In this study, scientific articles were examined to better understand factors related to SBCs internationally. National crash databases are another potential data source for forming a better outlook on the size of the problem and crash-related factors, but accessible data sources including necessary information are not always available. Hospital or emergency department data is typically needed to estimate the number of SBCs leading to injuries, because other data sources often exclude some SBC cases. These databases are not complete data sources either, as they typically contain limited information on the crash circumstances and other crash-related factors. Hence, analysing police-reported data with other data sources is also important (Schepers et al., 2015). For instance, coordinates of the crash site are important information for local authorities to be able to consider targeted safety improvements (Imprialou, Quddus, Pitfield, & Lord, 2016). Surveys or interviews can be used to complement other data sources.

Building high-quality and regularly maintained bicycle infrastructure to separate cyclists from motor vehicle traffic cannot be the only infrastructure-related solution to increase cycling safety, because SBCs have been identified as a key cause of injury in addition to collisions with motor vehicles (Ohlin et al., 2019). It is evident that more resources should be allocated to prevent SBCs as a potentially rising safety concern when the mode share of cycling increases. At the same time building cycle paths to separate cyclists from motor vehicles on high-volume roads is also necessary and this funding should not be reduced when additional funding is allocated to prevent SBCs. Especially, results on the main characteristics of SBCs indicate that more resources should be allocated to the avoidance of slippery conditions and loss of control cases. The high-quality maintenance of cycle paths is evidently among the key measures to prevent SBCs, but the responsibility of cyclists in terms of safe cycling behaviour should not be forgotten (Beck et al., 2016; Hosseinpour et al., 2021). The high proportion of crashes due to loss of controls or slippery conditions does not imply that infrastructure (e.g. slippery conditions due to poor road maintenance) or the cyclist (e.g. too fast speed in the circumstances) are solely responsible for the crash. It is likely that many of these cases are related to the combination of different contributing factors, as is addressed by Gildea et al. (2021) and Olesen et al. (2021). As the SBCs are typically associated to different factors, diverse actions are needed to prevent these cases (Beck et al., 2019).

While this research has identified key factors associated with SBCs and the prevalence of these cases there are several noted limitations. The literature review was based on scientific articles searched by several logical search terms in different databases, but it is possible that all the relevant studies were not captured. In addition, grey literature was not searched, because the focus of this study was on scientific articles. Inclusion of further studies may vary the results. In addition, national crash databases were not accessed directly, but we analysed the data described in the studies. It was assumed that the authors of the studied articles have applied the best available data and they have better knowledge on the available crash data from the studied countries than the authors of this study and hence, we decided to apply results reported in the scientific articles instead of asking original data from authorities or other institutes in different countries. However, future research should also access national databases, as they may provide more detailed data or larger samples. It should also be noted that most articles discussed in section 3.2. regarding the characteristics of SBCs are based on surveys or self-reporting, which is why some SBCs may be missing from the analysis. This may cause bias in the results depending on the analysed data included in the respective studies.

4. Conclusions

SBCs are typically underreported in road crash statistics and hence, the exact size of the problem is unknown. According to the literature review, the proportion of SBCs in injured cyclists (17–85%) varies heavily in different studies and data sources. However, the largest and most comprehensive data samples indicate that SBCs is the prevailing crash type among injured cyclists, as the proportion varies between 52% and 85% in these studies. Compared to the previous literature review on SBCs made by Schepers et al. (2015), which included statistics up to 2013, the proportion of SBCs does not seem to have changed notably. The analysis on the association between the proportion of SBCs and the mode share of cycling suggested that generally as the mode share of cycling increases so does the proportion of SBCs.

SBCs are most typically related to skidding or loss of control. High-quality and better maintained bicycle infrastructure is needed to promote cyclist safety, but this is not enough to guarantee safe cycling. It is also important to emphasise safe speed and behaviour while cycling. Road design and the technical features of the bicycle can also be enhanced.

Given the Safe System framework, future research should focus on the fact that SBCs are commonly the result of several contributing factors. For example, in the case of skidding on a slippery road surface, there may be other factors, such as issues with the bicycle, rider behaviour, interactions with other road users, or travel speed that could be important to identify. Therefore, more efforts should be made to analyse the interplay between SBC-related factors such as the infrastructure, the cyclist and other road users, and the bicycle. Similarly, it is important that policy makers adopt the Safe System approach to cyclist safety that considers different factors which also helps improve cyclist safety more broadly than just for SBCs. Since the results suggest that infrastructure is associated to a large proportion of SBCs, the behaviour of cyclists in different infrastructure and road conditions should be further investigated by surveys and naturalistic cycling studies to better understand the causes of SBCs. In addition, as colliding with an object is a typical factor related to SBCs and not many studies have investigated the avoidance of an object, the type of objects and their locations should be further studied to better understand safer road design.

This suggestion for future research also relates to the need for better crash data, which captures the range of crash-related factors and injury outcomes. One option to acquire better data is data linkage, where police, hospitals and insurance companies can link cases and combine their datasets. This would provide a larger dataset and potentially higher quality data for authorities, traffic safety experts and researchers.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Roni Utriainen http://orcid.org/0000-0002-2466-9660

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Appendix A

Table A1. The share of SBC victims in injured cyclists and the mode share of cycling based on the distribution of trips in different countries with more than 1,000 analysed SBCs regarding all ages and bicycle types in one study presented in Table 2.

Country	Number of studies in each country presented in Table 2	Sum of SBC victims	Sum of injured cyclists	Share of SBCs	The mode share of cycling (per cent of trips)
Sweden	2	40,945	51,237	80%	10% (Svensk Cykling, 2018)
Finland	1	6,651	9,268	72%	8% (Finnish Transport and Communication Agency, 2018)
The Netherlands	2	52,451	76,745	68%	27% (Harms & Kansen, 2018)
Norway	1	1,053	1,543	68%	5% (Strand, Nenseth, & Christiansen, 2015)
Denmark	2	4,013	7,536	53%	17% (Christiansen & Baescu, 2020)

Note: When more than one study in one country is available, the share of SBCs is based on the sum of analysed crashes in different studies. Note that the mode shares of cycling are from different years than the crash data.