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Systematic literature review of 10 years of cyclist safety research

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ABSTRACT

Cyclist safety is a research field that is gaining increasing interest and attention, but still offers questions and challenges open to the scientific community. The aim of this study was to provide an exhaustive review of scientific publications in the cyclist safety field. For this purpose, Bibliometrix-R tool was used to analyse 1066 documents retrieved from Web of Science (WoS) between 2012 and 2021. The study examined published sources and productive scholars by exposing their most influential contributions, presented institutions and countries most contributing to cyclist safety and explored countries open towards international collaborations. A keywords analysis provided the most frequent author keywords in cyclist safety shown in a word cloud with E-bike, behaviour, and crash severity representing the primary keywords. Furthermore, a thematic map of cyclist safety field drafted from the author's keywords was identified. The strategic diagram is divided in four quadrants and, according to both density and centrality, the themes can be classified as follows: 1) motor themes, characterized by high value of both centrality and density; 2) niche themes, defined by high density and low centrality; 3) emerging or declining themes, featured by low value of both centrality and density; and 4) basic themes, distinguished by high centrality and low density. The motor themes (i.e., the main topics in cyclist safety field) crash severity and bike network were further explored.

The research findings will be useful to develop strategies for making bike a safer and more confident form of transport as well as to guide researchers towards the future scientific knowledge.

1. Introduction

Each year road crashes cause 1.35 million deaths, and most fatalities are among vulnerable road users (VRUs): pedestrians, cyclists and motorcyclists (WHO, 2018). Cyclists are relatively vulnerable, especially if compared to vehicle occupants.

Mode of active travel, such as cycling, contribute to creating a habitable environment and improve accessibility for all road users. However, on the world's roads about 41 000 cyclists are killed every year (WHO, 2018). This is, in part, a result of rapid increases in motorization followed by a road system mostly designed considering vehicular traffic needs neglecting cyclists too many times in land use planning with serious consequences for their safety (Sipos, 2014). Recognizing the importance of the problem, through UN General Assembly, governments from around the world have been trying to reverse the trend. The UN General Assembly Resolution 74/299 proclaims the period 2021–2030 as the Second Decade of Action for Road Safety, with a goal of reducing road traffic deaths and injuries by at least 50 per cent from 2021 to 2030, identifying cyclist safety as a key priority (United Nations, 2020). Great emphasis on cyclists' safety is also given in the EU Road Safety Policy Framework 2021–2030 which suggests less car use in cities combined with safer environments for cyclists to develop the synergies between safety and sustainability measures (European Commission, 2021a). Although the benefits of cycling are noted (Beck et al., 2022; Celis-Morales et al., 2017) there are concerns that an increased uptake of cycling as a mode of transport may result in higher rate of crashes involving bicycles, even if some studies suggest a possible safety-in-numbers effect (Fyhri et al., 2017; Jacobsen, 2003).

Cyclist' safety has long been a critical area of road safety research and is an area that is receiving increasing attention (Salmon et al., 2022). A starting point for expanding the knowledge base on cyclist safety is to carry out a systematic literature analysis to highlight research

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directions as well as existing research gaps. Understanding the state-of-the-art is a powerful strategy to orient the research and identify topics on which further research would be beneficial (Aria et al., 2020). Nevertheless, scientific research itself as well as recording and spreading research results through publications and papers has become complex. The overwhelming number of scientific papers on a specific area and their complexity have reached so high level of investigation and exploration that personal knowledge and experience are no longer sufficient tools for understanding future research trends and for collecting the most relevant information. Thus, the need to be selective and able to highlight significant or promising areas of research to explore has become essential.

Among the several approaches to organize the existing knowledge base, Bibliometrix has been proposed and designed by Aria and Cuccurullo (2017) as a tool to introduce a systematic, transparent, objective, reliable and reproducible review process based on the statistical measurement of science, scientists, or scientific activity (Aria et al., 2020). Bibliometrix tool was used in disparate science fields such as information technology (Yang et al., 2019), med (de Vasconcelos Silva et al., 2022; Zhao and Strotmann, 2010), psychology (Weleff et al., 2021), business and finance (Janbaz et al., 2022; Lillo et al., 2020), economic (Kaur et al., 2022), agriculture (Zakaria et al., 2022), biochemistry (de Oliveira Barbosa and Galembeck, 2022), physic (Bitzenbauer, 2021), sociology (Monteagudo-Fernández et al, 2021), low (Prins and Reich, 2021), political science (Cepiku and Mastrodascio, 2021), and geology (Song and Wu, 2021).

In this paper, Bibliometrix was used to carry out a systematic literature review (SLR) of 10 years of cyclist safety research. Several research reviews have been conducted overtime but according to our knowledge bibliometric methods to analyse the cyclist safety have not yet been used. By using the methodology developed by Aria and Cuccurullo (2017), our study provided a macroscopic overview on the main aspects of publications in the interest field based on a bibliometric analysis by highlighting emerging topics and identifying the evolution and geographic distribution of cyclist safety research worldwide. The bibliometric analysis was scaled to evaluate cyclist safety impact in terms of research produced at different levels: countries, organizations, and individuals. The aim of this review is to offer a logical first step in establishing directions for future progress and assessing which research questions have not been answered yet as well as the existence of research gaps that should be addressed and better investigated to create a safer environment for cyclists.

2. Method

2.1. Overview

The quality of metrics used to conduct a study depends on quality of the employed data. That is why the source material must be of high quality. Furthermore, it is essential that data reflect three main attributes: consistent, authoritative, and clearly defined so that it is possible to create meaningful and dependable statistics. We choose WoS Core Collection (at http://www.webofknowledge.com) as search engine due to its database with large volume of scientific data, which contain the records of the world's most impactful and high-quality journals (Li and Hale, 2016). WoS is the oldest citation database and includes different citation databases with useful information collected from journals, conferences, reports, books, and book series (Yunus et al., 2013). The Journals included in WoS meet high standards of quality and impact thanks to a careful selection process based on a set of 28 criteria: 24 quality criteria to evaluate editorial rigor and best practice at the journal level and 4 impact criteria to identify the most influential journals in their respective fields. These are subject to continuous curation, so that if a journal decreases in quality will be removed from WoS Collection automatically.

2.2. Data collection

Data collection can be divided into 2 phases. The first is data retrieval while the second consists of data cleaning. The data used in this study were sourced from WoS at http://www.webofknowledge.com on July 26th, 2022. After accessing WoS, five steps were followed for constructing the database for the SLR of cyclist safety. Initially, all the documents published between 2012 and 2021 relating to WoS categories "Transportation Science & Technology", "Transportation" "Engineering", "Civil" and "Environmental" were selected, obtaining 683,292 results. Then, additional filters were applied to refine the document research. A filter was applied to select documents containing a cyclist-related word in the title (filter 1). The topic section was refined by using the keywords safety, crash, accident, and collision (filter 2). WoS topic section extends the search to the title, the abstract, the author's keywords, and the keywords plus (note that keywords plus are words or phrases that frequently appear in the titles of an article's references but do not appear in the title of the article itself). Finally, two more filters were applied respectively to the language (filter 3) and the document type (filter 4). The refinement regards the selection of articles, books or book chapters, proceedings papers and reviews written in English only. Below, a summary of data-collection steps and filter is provided:

1. WoS Categories: Transportation Science & Technology OR Transportation OR Engineering, Civil OR Environmental
Year Published: 2012 – 2021
2. Title: Cyclist* OR Bicyclist* OR Bike* OR Bicycle* OR Vulnerable*
3. Topic: Safety OR Crash* OR Accident* OR Collision*
4. Language: English
5. Document Type: Article, Book, Book Chapter, Proceedings Paper, Review

where "OR" is a boolean operator used to find records containing certain words from our search and "*" is a jolly symbol that means any character used to break off the query words and have more control over retrieval of plurals and variant spelling.

The final database included 1066 bibliographic records. Each record contains several bibliographic attributes, such as authors' names, title, source, times cited count, accession number, authors identifiers, ISSN, abstract, addresses, affiliations, document type, keywords, WoS category, research areas, cited references, cited references count, hot papers, and highly cited papers.

After an in-depth analysis, it was found that almost all the articles had at most 5 keywords. Thus, the first 5 keywords of each selected article were analysed and processed for uniformity among papers when necessary. Different papers used the same keyword, some with singular from and others with plural extension. So, the plural word was replaced with its singular form. Also, the synonyms were replaced with the same word. For example, the author keywords replaced with the new keyword "e-bike" were electric bicycle, electric-bicycle, electric bike, e-bicycles, electric bicycles, electric power assisted bicycles, e-bikes, electric bicycle riders, electric assist bikes, e-cyclists, delivery e-bike, electric bike riders, electrically power assisted bicycle, e-bicycling, fast e-bikes, electric-bike (or e-bike), and electric-assisted bicycles.

2.3. Data analysis

Many systematic approaches currently help researchers to identify relevant literature to understand and organize earlier findings (Chabowski et al., 2011; Glänzel, 2003; Valenzuela-Fernandez et al., 2019). For instance, the bibliometric analysis is a set of methods which allow to provide a macroscopic overview of large amounts of academic literature by presenting the knowledge status and research trends in the exploration field (Aria et al., 2022; Jones, 2016; Toom, 2018; van Eck et al., 2010; Xie et al., 2020). The overwhelming volume of new information, conceptual developments, and data are the environment where the bibliometric analysis becomes useful. Most of the tools supporting the bibliometric analyses are frequently available only under commercial licenses and their use is linked to users' ability in terms of programming skills (Guler et al., 2016). Bibliometrix tool is an open-software nature, developed in the R language and follows a classic logical bibliometric workflow. R is a language and environment for statistical computing and graphics, which offers the opportunity of automating analyses and set up new functions. As it is programmed in R, Bibliometrix tool is adaptable and can be rapidly upgraded, ideal for a constantly changing field such as the bibliometric analysis (Ferreira-Vanegas et al., 2022; Rodrìguez-Soler et al., 2020).

Bibliometrix offers procedures to import a database of bibliographic records executing bibliometric analysis and construct data matrix for co-citation, coupling, scientific collaboration analysis and co-word analysis. It further provides the users with a web-based app, Biblioshiny, for a user-friendly interface. Biblioshiny is formulated in the Shiny environment and integrates the Bibliometrix package functionality with the comfort of use of web apps.

With the aim of investigating the interest in cyclist safety, the annual trend of publications from 2012 to 2021 and the compound annual growth rate (CAGR), i.e., the geometric progression ratio that gives a constant rate over the time, were evaluated. Bibliometric review covers three different level metrics: sources, authors, and documents. At source level, the source relevance was assessed by the number of documents published in our collection.

The author's analysis is useful to detect the individuals who most published about cyclist safety to follow their search evolution and future directions (Cuccurullo et al., 2016). Furthermore, author's affiliation and country were analysed.

The last level metric analysed was related to scientific documents included in a bibliographic collection. At first, we measured the impact of a document in the whole bibliographic database through the citation. Garfield (1979) defined the citation count a measure of utility rather than a measure of the importance or impact of scientific works. So that, a highly cited document is one that collectively has been found to be useful by many researchers or in a relatively large number of analyses.

Our study has focused, then, on the author keywords which consist of a list of terms that authors believe best represent the content of their paper. The analysis of the author's keywords is a fundamental tool to find out trending themes and scholars' priority in the field (Song et al., 2019; Agbo et al., 2021). After identifying the top author keywords by occurrence, a word cloud was created as a useful graph which allows an immediate understanding of the most significant keywords through font size and colour of each word. To highlight the knowledge development and structural relationships and to present correlational research, Knowledge mappings were designed.

2.4. Data visualization

Knowledge mapping allows visualizing the structural and dynamic aspects of scientific research from a statistical point of view (Börner et al. 2003;Morris and Van Der Veer Martens, 2008 Not only is science mapping analysis able to reveal the intellectual connections within the dynamically changing system of scientific knowledge, but it can also stimulate the creation of new knowledge in the overall knowledge groups (Small, 1997; Zou et al., 2020). Drawing an informative and easy to interpret graphical representation of scientific knowledge has always been useful to researcher of different fields. Indeed, knowledge mapping usage is considerably increasing (Zou et al., 2020; Aria et al., 2020; Sarkara and Maitib, 2020; Ferreira-Vanegas et al., 2022).

A world map is a geographical representation of the collaboration network of an author's country.

Based on the keyword network, it is possible to plot the keywords on the thematic map in accordance with two measures known as centrality and density (Callon et al., 1991; Cobo et al., 2011). These two properties give information about development and importance of a theme.

3. Results

The search across WoS Core Collection provided 1,066 records that deal with cyclist safety.

Fig. 1 summarizes the data collection working flow used to select the elements in the retrieved sample that defined the final database used in this study. The search strategy was defined by a combination of filters that are terms linked by Boolean operators allowing to choose what kind of documents to analyze.

3.1. Publication trend of papers addressing cyclists' safety

The cyclist safety is gradually gaining the attention of researchers, practitioners, and academicians across the world (Fig. 2). The research traced back in the year 2012 with a very small number of publications (48 documents) and showed an increasing trend with 169 documents published in 2021 only and exhibiting an average annual growth equal to 15.1 %. The trend of cyclist safety studies is therefore clear, showing a dramatic increase of the interest in cycle safety. The reasons of this exigency could be that while stronger active mobility policies are raising, the emerging mobility choices also need to take safety considerations into account systematically (WHO, 2018).

3.2. Source

A source is a journal/book/conference proceedings series/etc. which published documents included in the data collection under study. The database used in the study has 171 sources. The ten most relevant sources are reported in Table 1. The relevance of each source was evaluated according to the number of documents published during the analysed decade and the source Impact Factor (IF) achieved in 2021. IF is a measure of the frequency with which the "average article" in a journal has been cited in a particular year or period. The most relevant source is Accident Analysis and Prevention with more than 22 % of the cyclist safety research published in this journal (% documents = 22.14; IF = 6.376). Transportation Research Part F-Traffic Psychology and Behaviour provides the second-highest contribution (% documents = 8.91; IF = 4.349). Of minor impact but still of considerable influence, there are sources such as Traffic Injury Prevention (% documents = 8.63; IF = 2.183), Transportation Research Record (% documents = 4.13; IF = 3.613), Journal of Transport & Health (% documents = 4.13; IF = 3.613), Journal of Safety Research (% documents = 3.47; IF = 4.264), Transportation Research Part A-Policy and Practice (% documents = 1.88; IF = 6.615), Journal of Transportation Safety & Security (% documents = 1.78; IF = 2.825), International Journal of Sustainable Transportation (% documents = 1.69; IF = 3.963), Journal of Transport Geography (% documents = 1.59; IF = 5.899). The top 10 journals contributed 62.76 % of the analysed papers.

3.3. Authors

Table 2 presents the ten most relevant authors. The authors have been ranked according to their total number of publications and their total citations in the dataset analysed. In this analysis, no distinction has been made between lead author, corresponding author, and other author role. Thus, an author appearing in "n" documents contributed to "n" document, regardless the role. Haworth Narelle (Queensland University of Technology, Australia) and Sayed Tarek (University of British Columbia, Canada) were the top of the list contributing to 18 papers. Then, Abdel-Aty Mohamed (University of central Florida, USA) and Dozza Marco (Chalmers University of Technology, Sweden) followed with 15 documents. Other scholars made remarkable contributions such as Tohnson Marilyn (Monash University, Australia), Guo Yanyong (Southeast University, China), O'Hern s Steve (Monash University, Australia), Prati Gabriele (University of Bologna, Italy), Winters Meghan (Simon Fraser University, Canada), and Cai Qing (University of Central

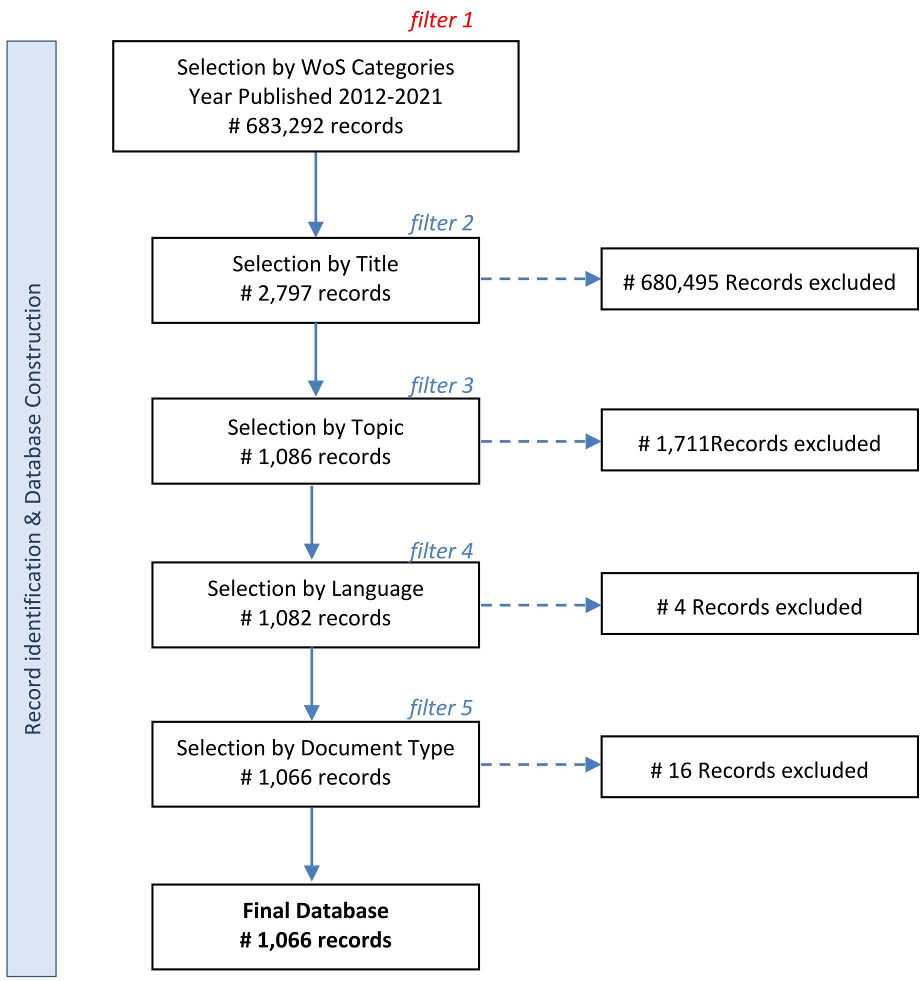


Fig. 1. Data collection workflow.

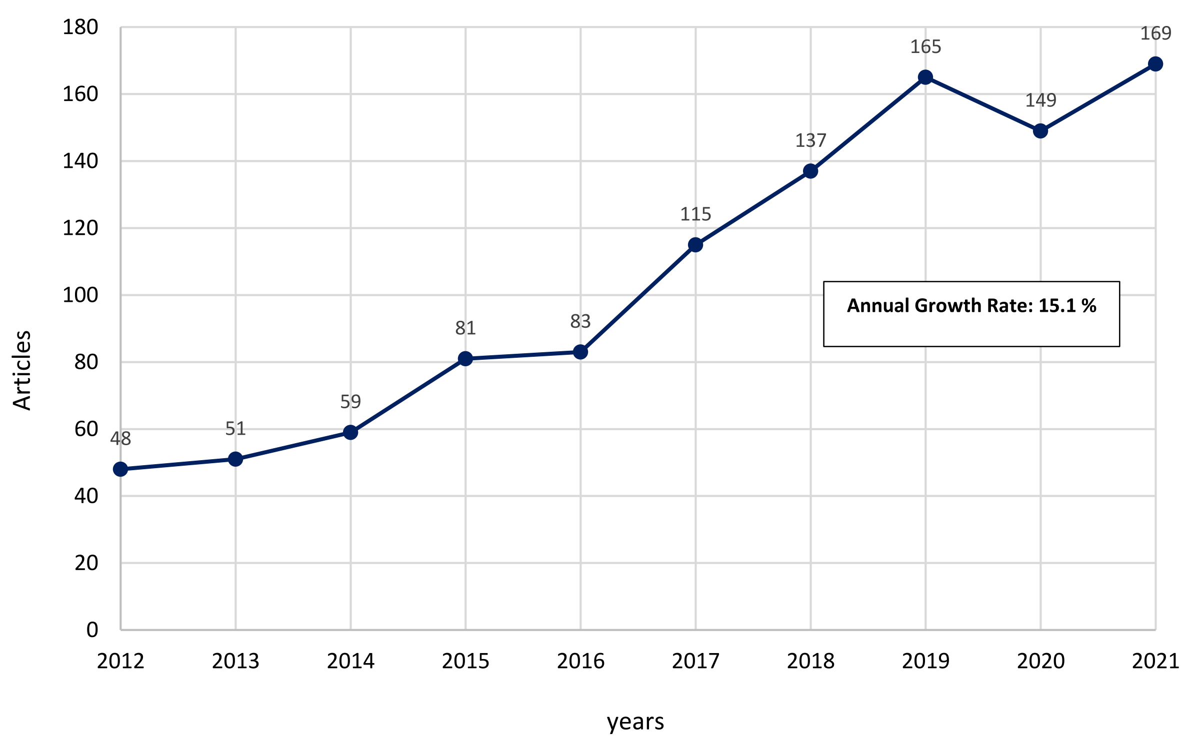


Fig. 2. Annual scientific production.

Table 1
The ten most relevant sources per number of documents.

Sources	# of documents	% of documents	2021 IF
Accident Analysis & Prevention	236	22.1	6.376
Transportation Research Part F-Traffic Psychology and Behaviour	95	8.9	4.349
Traffic Injury Prevention	92	8.6	2.183
Transportation Research Record	91	8.5	2.019
Journal of Transport & Health	44	4.1	3.613
Journal of Safety Research	37	3.5	4.264
Transportation Research Part A-Policy and Practice	20	1.9	6.615
Journal of Transportation Safety & Security	19	1.8	2.825
International Journal of Sustainable Transportation	18	1.7	3.963
Journal of Transport Geography	17	1.6	5.899
Sum of the ten most relevant sources	669	62.8	–
Total database	1066	100.0	–

Abbreviations: IF = Impact Factor.

Table 2
The ten most productive authors in cyclist safety.

Authors	Institution	Country	Documents	TC
Narelle Haworth	Queensland University of Technology	Australia	18	383
Tarek Sayed	University of British Columbia	Canada	18	250
Mohamed Abdel-Aty	University of central Florida	United States	15	529
Marco Dozza	Chalmers University of Technology	Sweden	15	349
Marilyn Tohnson	Monash University	Australia	12	239
Yanyong Guo	Southeast University	China	10	209
Steve O'Hern s	Monash University	Australia	10	83
Gabriele Prati	University of Bologna	Italy	10	209
Meghan Winters	Simon Fraser University	Canada	10	119
Qing Cai	University of Central Florida	United States	9	201

Abbreviations: TC = Total Citations that represent the number of times an author is cited in all sampled documents.

Florida, USA). Moreover, Abdel-Aty Mohamed could be also considered the most significant publishing author since, in our data-collection, he classified first in the total citation category having obtained 529 total citations (roughly 35 citations per paper), followed by Dozza Marco (15 documents cited 349 times, roughly 23 citations per paper) and Haworth Narelle (383 citations, 22 citations per paper).

3.4. Most productive institutions

Table 3 shows the 10 most productive affiliations in cyclist safety associated with their country and for each university the Quacquarelli Symonds (QS) rank position was provided. The QS World University ranking is an annual publication ranking over 1,500 institutions around the world. The ranking compares institutions on different criteria: from the academic reputation to the number of international students. Among the top 10 institutions, 9 are universities and 1 is an Institute for Road Safety Research.

Monash University has the highest number of publications equal to 62 documents, followed by the Queensland University of Technology (40), University of British Columbia (40), Delft University of Technology (35), Southeast University (35), Chalmers University of Technology (30), Tongji University (28), SWOV – Institute for Road Safety Research (25), McGill University (24) and University of North Carolina (24). Four Institutions are in the northern Europe such as Delft University of Technology (Netherlands), Chalmers University of Technology (Sweden), SWOV – Institute for Road Safety Research (Netherlands), and McGill University (Sweden). This may not be a casualty but may reflect the need for a safer cyclists' environment in accordance with the habits of the locals.

Table 3
The ten most productive affiliations in cyclist safety.

Affiliation	Country	Documents	QS Rank 2021
Monash University	Australia	**62**	**55**
Queensland University of Technology	Australia	40	217
University of British Columbia	Canada	40	45
Delft University of Technology	Netherlands	35	57
Southeast University	China	35	493
Chalmers University of Technology	Sweden	30	139
Tongji University	China	28	256
SWOV – Institute for Road Safety Research	Netherlands	25	n.a.*
McGill University	Sweden	24	31
University of North Carolina	United States	24	95

* Not University.

Furthermore, Table 3 reveals that the ten most productive affiliations in cyclist safety research are among the top 500 universities according to the QS World University Ranking.

3.5. Most productive countries

The ten most productive countries were listed in Table 4. For each of them, the single country publications, multiple countries' publications, and total citations were marked to identify the most fruitful collaborations and their impact on cyclist safety research. The top ten productive countries contributed approximately 77 % of the publications in the database. Considering the number of publications and the total citations, the leading countries were the USA (% Documents = 24.11, 3,914 citations) followed by China (% Documents = 11.36, 1,598 citations), Australia (% Documents = 9.85, 2,309 citations) and Canada (% Documents = 6.75, 1,180 citations). There was also a considerable scientific production in Europe. Indeed, a large number of documents in cyclist safety field were published by Netherlands, Sweden, Germany, and United Kingdom and a fairly large number of documents were published by Italy and Norway. These findings were confirmed by world map (see Fig. 3) through the intensity of blue colour. In China, USA, Australia, Netherlands, Sweden and United Kingdom, scholars demonstrated active collaborations with international institutions and universities producing several documents with the involvement of at least one co-author from a different country. Conversely, Norway, Germany, and Italy had low interaction worldwide. Using different link sizes, the world

Table 4
Country production, collaborations, and citations.

Country	Documents	%Documents	SCP	MCP	TC
USA	257	24.11	224	33	3,914
China	124	11.63	83	41	1,598
Australia	105	9.85	81	24	2,309
Canada	72	6.75	58	14	1,180
Netherlands	53	4.97	34	19	957
Sweden	51	4.78	38	13	902
Germany	49	4.60	41	8	357
United Kingdom	47	4.41	34	13	646
Italy	36	3.38	27	9	357
Norway	23	2.16	18	5	337

Abbreviations: SCP = Single Country Publication, MCP = Multiple Countries Publication that indicates, for each country, the number of documents in which there is at least one co-author from a different country, hence measures the international collaboration intensity of a country.

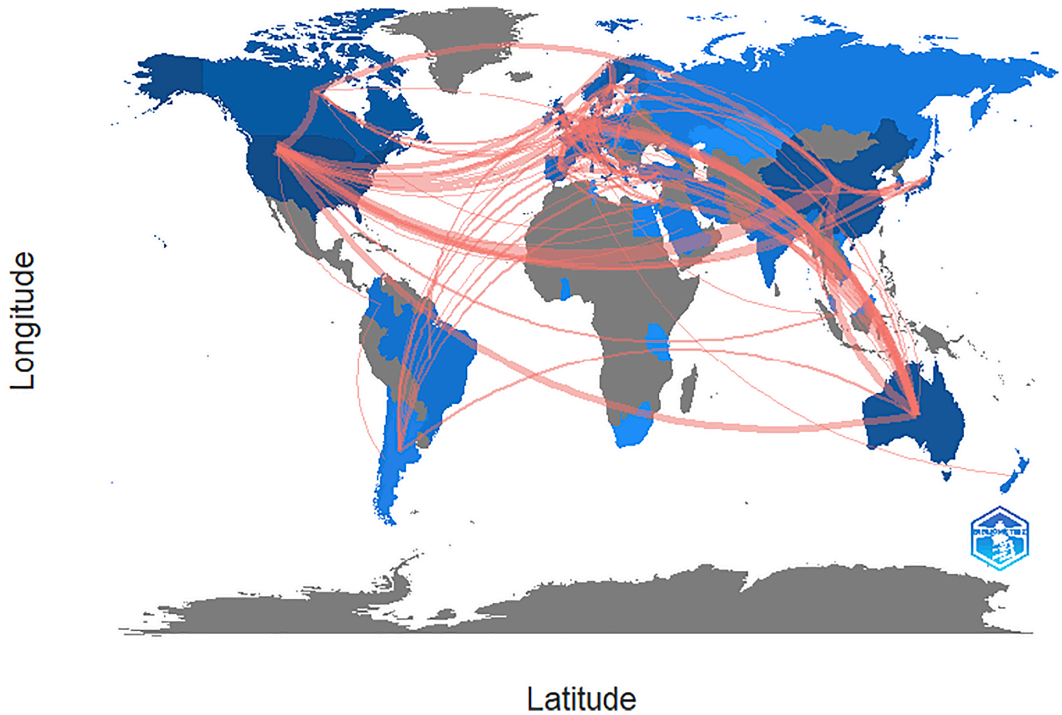


Fig. 3. Collaboration world map. The colour intensity is proportional to the number of publications whereas the size edge increases when the strength of collaboration between two joined countries increases.

map also gave a clue about the most open countries towards active collaborations. The most frequently international collaborations highlighted by very large links, were from USA to China and Canada, and from Australia to Netherlands and United Kingdom. The USA scholars had the most dynamic scientific production, demonstrating of being more likely to collaborate with authors of other countries in forward-looking research activities. In the period 2012–2021, the USA researchers produced scientific documents with authors from 25 different countries. In China and Australia researchers showed a positive attitude towards active international collaborations, collaborating with authors from 15 and 29 different countries respectively.

3.6. Most cited documents

Highly cited papers are those that have had a strong influence in the development of the cyclist safety research area. Furthermore, they are believed to indicate research hotspots during certain periods. Our data-collection contained documents dealing with cyclist safety even when cyclist safety wasn't the main theme. After a detailed reading, in this section we selected only documents in which cyclist safety was the main topic. Besides, the documents have been ranked according to total citation per year and the top twenty are reported in Table 5.

Among the top twenty most-cited papers, fourteen documents have been published in Accident Analysis and Prevention, two documents in Analytic Methods in Accident Research and one in Transport Reviews, Traffic Injury Prevention, Transportation Research Part F, and Journal of Safety Research.

The paper with the highest number of citations per year was "Determinants of bicyclist injury severities in bicycle-vehicle crashes: A random parameters approach with heterogeneity in means and variance" (Behnood and Mannering, 2017). The authors explored the risk factors that significantly contribute to the bicyclist injury severity showing that many factors potentially affect the bicycle/motor-vehicle crash severity, including bicyclist and driver race and gender, alcohol-impaired bicyclists or drivers, older bicyclists, riding or driving on the wrong side of road, drivers' unsafe speeding, bicyclist not wearing helmet, and so on. The findings of this research point towards the need for further studies investigating the contributing factors to the bicyclist injury severities. The need to fill this gap has led scholars to focus on factors explaining the severity of cyclist crashes and the highly cited documents (Table 5) used different statistical models, such us CHAID decision tree technique and Bayesian network (Prati et al., 2017), generalized ordered logit models and generalized additive models (Chen and Shen, 2016), and Bayesian multivariate models (Heydari et al., 2017).

Different impactful papers highlighted the importance of considering the spatial effects (Amoh-Gyimah et al., 2016; Cai et al. 2016; Chen and Shen, 2016; Guo et al., 2018a; Siddiqui et al. 2012). For example, Siddiqui et al. (2012) investigated the effect of spatial correlation using a Bayesian spatial framework to model pedestrian and bicycle crashes in traffic analysis zones. Cai et al. (2016) analysed pedestrian and bicycle crash frequency comparing dual-state models such as zero-inflated negative binomial and hurdle negative binomial models (with and without spatial effects) with the conventional single-state model (i.e., negative binomial). The model comparison revealed that the model with spatial effects offered the best performance. Similarly, Amoh-Gyimah et al. (2016) found that models accounting for the spatial autocorrelation of bicycle crash data performed better than the non-spatial models. Guo et al. (2018a) explored factors that contribute to cyclist crash frequency by developing four different models such as Poisson lognormal (PLN), random intercepts PLN, random parameters PLN, and spatial PLN models. Among them, the spatial PLN model had the best goodness of fit, and the results highlighted the significant effects of spatial correlation.

To develop safety performance functions for bicycle crashes, the recording of the cycling exposure is essential. Using exposure and crash data, de Geus et al. (2012) found that cyclists involved in a crash cycle faster and cycle a greater distance per week compared to those not involved in an accident.

The use of electrically bicycles is rapidly increasing in the recent years. E-bikes are an emergent new transportation mode. Therefore, their role in transportation systems and their impact on users have become important issues for policy makers and engineers. Five papers

Table 5
The twenty most global cited documents.

Title	Authors	Year	Source	TC/Y	TC
Determinants of bicyclist injury severities in bicycle-vehicle crashes: a random parameters approach with heterogeneity in means and variance	Behnood, A., Mannering, F.	2017	Anal. Methods Accid. Res.	29.50	177
Macroscopic spatial analysis of pedestrian and bicycle crashes	Siddiqui,C., Abdel-Aty, M., Choi, K.	2012	Accid. Anal. Prev.	18.18	200
Macro-level pedestrian and bicycle crash analysis: incorporating spatial spill over effects in dual state count models	Cai, Q., Lee J., Eluru, N., Abdel-Aty, M.	2016	Accid. Anal. Prev.	16.86	118
Exploring unobserved heterogeneity in bicyclists' red-light running behaviors at different crossing facilities	Guo, Y., Li, Z., Wu, Y., Xu, C.	2018	Accid. Anal. Prev.	15.40	77
Bicycle helmets - to wear or not to wear? A *meta*-analysis of the effects of bicycle helmets on injuries	Hoye, A.	2018	Accid. Anal. Prev.	14.00	70
In search of surrogate safety indicators for vulnerable road users: a review of surrogate safety indicators	Johnsson, C., Laureshyn, A., De Ceunynck, T.	2018	Transp. Rev.	13.20	66
The red-light running behavior of electric bike riders and cyclists at urban intersections in China: an observational study	Wu, C., Yao, L., Zhang, K.	2012	Accid. Anal. Prev.	12.82	141
The safety of electrically assisted bicycles compared to classic bicycles	Schepers J.P., Fishman E., Den Hertog, P., Wolt, K., Schwab, A.	2014	Accid. Anal. Prev.	12.78	115
Perceived traffic risk for cyclists: the impact of near miss and collision experiences	Sanders, R.L.	2015	Accid. Anal. Prev.	12.00	96
A cross-comparison of different techniques for modelling macro-level cyclist crashes	Guo, Y., Osama, A., Sayed, T.	2018	Accid. Anal. Prev.	11.80	59
Casualty risk of e-bike rider struck by passenger vehicle using China in-depth accident data	Hu, L., Hu, X., Wang, J., Kuang, A., Hao, W.,Lin, M.	2020	Traffic Inj. Prev.	11.33	34
Using data mining techniques to predict the severity of bicycle crashes	Prati, G., Pietrantoni, L., Fraboni, F.	2017	Accid. Anal. Prev.	10.67	64
Risky riding: naturalistic methods comparing safety behavior from conventional bicycle riders and electric bike riders	Langford, B., Chen, J., Cherry, C.	2015	Accid. Anal. Prev.	9.63	77
Built environment effects on cyclist injury severity in automobile-involved bicycle crashes	Chen, P., Shen, Q.	2016	Accid. Anal. Prev.	9.43	66
Using naturalistic data to assess e-cyclist behavior	Dozza, M., Piccinini, G.F.B., Werneke, J.	2016	Transp. Res. Pt. F-Traffic Psychol. Behav.	9.29	65
How do drivers overtake cyclists?	Dozza, M., Schindler, R., Bianchi-Piccinini, G., Karlsson, J.	2016	Accid. Anal. Prev.	9.29	65
Safety impacts of bicycle infrastructure: a critical review	Digioia, J., Watkins, Ke., Xu, Yz., Rodgers, M., Guensler, R.	2017	J. Saf. Res.	9.17	55
Using a flexible multivariate latent class approach to model correlated outcomes: a joint analysis of pedestrian and cyclist injuries	Heydari, S., Fu, L., Miranda-Moreno, L., Jopseph, L.	2017	Anal. Methods Accid. Res.	9.17	55
Macroscopic modelling of pedestrian and bicycle crashes: a cross-comparison of estimation methods	Amoh-Gyimah, R., Saberi, M., Sarvi, M.	2016	Accid. Anal. Prev.	9.14	64
A prospective cohort study on minor accidents involving commuter cyclists in Belgium	De Geus, B., Vandenbulcke,G., Int Panis, L., Thomas, I., Degraeuwe,B., Cumps,E., Aertsens,J., Torfs, R., Meeusen, R.	2012	Accid. Anal. Prev.	9.09	100

Abbreviations: TC = Total Citations that measures the number of citations a document has received from the other records contained in the entire database; TC/Y = Total Citation per Year.

related to safety implications of e-bikes have been highly relevant. Wu et al. (2012) investigated the rate, associated factors, and behaviour characteristics of cyclist' red-light running in China by using two synchronized video cameras at three signalized intersections. Several studies compared the electric and classical bicycles by highlighting that both bike users have very high violation rates of traffic control devices (Schepers et al., 2014). However, electric bicycle users are more likely to be involved in a crash that requires treatment at an emergency department (Langford et al., 2015). Moreover, the results suggest that safety countermeasures should be different for electric and traditional bicycles since electric bicycles are ridden faster than traditional bicycles and interact differently with other road users (Dozza et al., 2016a). Hu et al. (2020) investigated the association between e-bike rider casualty and impact speed ns based on China in-depth accident study data providing insights to formulate effective policies for speed limit management to improve the safety of e-bikes.

Among all crashes involving cyclists, a motorist who overtakes cyclist is particularly dangerous. Dozza et al. (2016b) examined the factors that most influenced the overtaking manoeuvre through 145 records of car and truck drivers that overtook an instrumented bicycle on public rural roads in Sweden.

Although the percentage of people bicycling for transportation rose during the last decade still only a small part of all trips is made by bicycle. Research suggests that the risks associated with bicycling near traffic were a significant barrier to widespread cycling (Sanders, 2015). One of the most significant risk factors is the bicyclists' red-light running at crossing facilities (Guo et al., 2018b), which was found to be mainly affected by gender, age, bicycle type, road width, presence of raised median, separation width, signal type, green ratio, bike and vehicle volume, and average vehicle speed.

Two reviews and a meta-analysis were also in the top twenty list of the most cited papers. Johnsson et al. (2018) provided a review of surrogate safety indicators for the analyses of critical traffic events involving VRU, while Digioia et al. (2017) examined safety literature relating to 22 bicycle treatments, including findings, study methodologies, and data sources used in the studies. Study findings highlighted that a wide range of different indicators can be used to identify safety critical events in traffic. However, no existing indicator which can capture all aspects. To reflect different aspects of traffic events the combinate use of various indicators is required. Digioia et al. (2017) showed that while the effectiveness of bicycle treatments such as bike lanes and removal of on-street parking has been confirmed, many treatments are still in need of rigorous research. Review conclusions could guide research efforts towards understanding suitable indicator for safety analyses based on crash records and safety impacts of bicycle infrastructure.

Høye (2018) carried out a meta-analysis of the effects of bicycle helmets on serious head injury and other injuries among crash involved cyclists, including 179 effect estimates from 55 studies from 1989 to 2017. The use of bicycle helmets was found to reduce head injury by 48 %, serious head injury by 60 %, traumatic brain injury by 53 %, face injury by 23 %, and the total number of killed or seriously injured cyclists by 34 %. These results are quite relevant since currently the use of bicycle helmets is not mandatory and is very low. The EU Road Safety Policy Framework 2021–2030 – Next steps towards "Vision Zero" (European Commission, 2021a) defines intermediate outcome targets based on Key Performance Indicators (KPIs) directly linked to reducing deaths and injuries and the KPI 3 includes cyclists wearing a protective helmet.

4. Keywords analysis

The keywords analysis was performed to evaluate the most frequent author keywords in cyclist safety. At this aim, the terms bike, safety, and crash were removed. These keywords were trivial as they were used to develop the extraction data query used to select the documents in the database. The most frequent author keywords in cyclist safety are illustrated in the word cloud in Fig. 4. The size of each word indicates its frequency and importance in our data-collection. E-bike, behaviour, and crash severity represented primary keyword by appearing in the keyword. Besides these words, risk, vulnerable road user, pedestrian, helmet, bikeshare, bike network and intersection were the most frequent themes in the cyclist safety studies. Keywords showed by word cloud help to identify the topic and focus of that publication quickly.

Thematic network was identified. Fig. 5 represents the thematic map of cyclist safety field drafted from the author's keywords. It allows to gain insight into the cyclist safety field's current status and its future directions. Thus, the analysis let the researchers know the thematic areas to focus on in future research. The strategic diagram contains themes characterized by density and centrality. The centrality symbolizes the importance of the theme in the entire research area, while the density represents a measure of the theme's development. The strategic

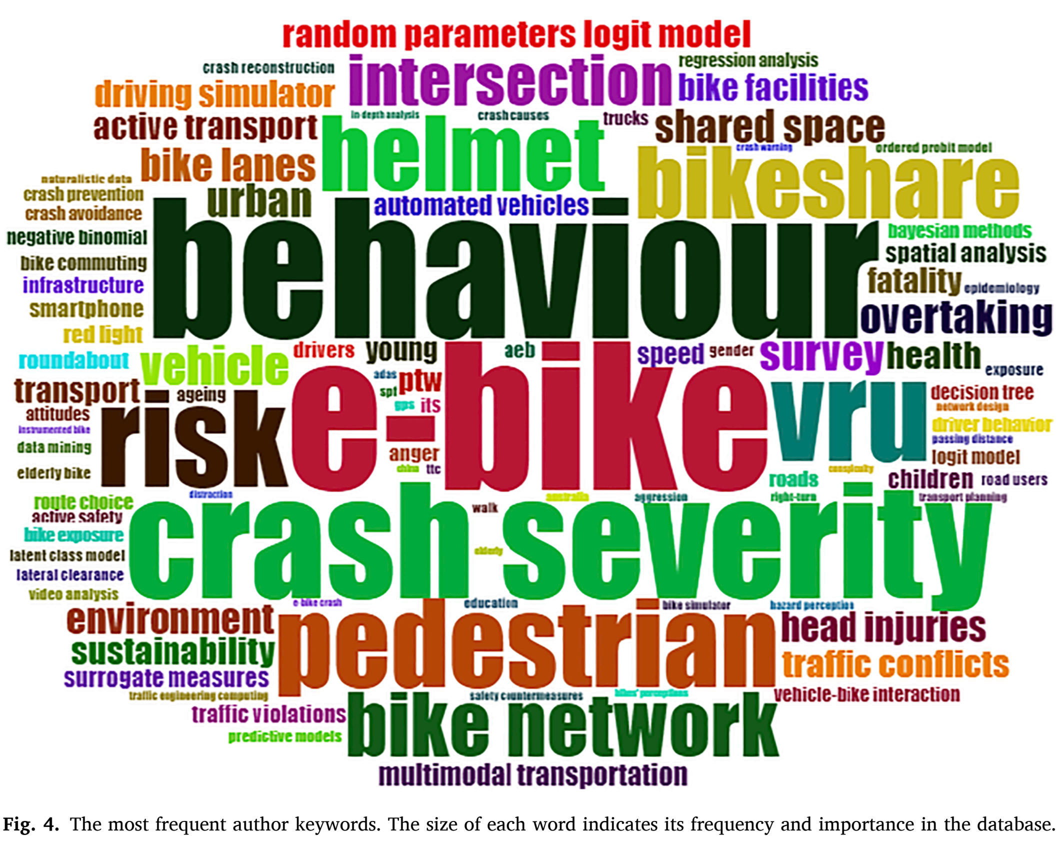
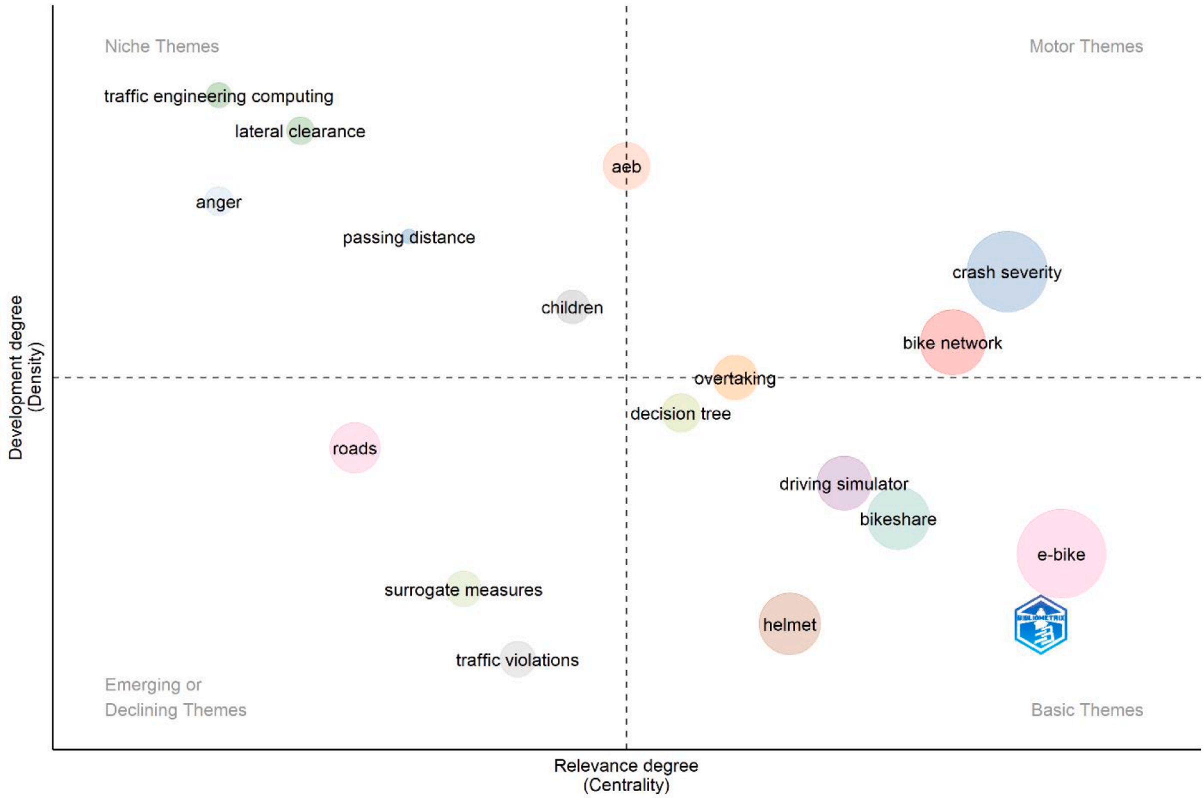


Fig. 4. The most frequent author keywords. The size of each word indicates its frequency and importance in the database.



Bike network: bike network, urban, bike lanes, bike facilities, infrastructure, network design, bikes' perceptions, instrumented bike, mathematical analysis.

Crash severity: crash severity, VRU, pedestrian, fatality, transport, PTW (Powered Two Wheelers), logit model, crash prevention, elderly cyclist, exposure, road users, crash causes, epidemiology, walk, conspicuity, e-bike crash, in-depth analysis, ordered logit model, safe system, underreporting.

Overtaking: overtaking, smartphone, distraction.

Driving simulator: driving simulator, automated vehicles, driver behavior, Intelligent Transport Systems (ITS), Advanced Driver Assistance Systems (ADAS), bike simulator, safety countermeasures.

Bikeshare: bikeshare, health, sustainability, active transport, gender, transport planning, physical activity.

E-bike: e-bike, behaviour, risk, intersection, vehicle, survey, shared space, environment, random parameters logit model, traffic conflicts, multimodal transportation, speed, spatial analysis, red light, roundabout, drivers, Bayesian methods, bike commuting, ageing, attitudes, regression analysis, GPS, naturalistic data, Australia, right-turn, China, elderly, naturalistic bike, micro-mobility, structural equation modelling.

Helmet: helmet, head injuries, young, crash reconstruction, education, TTC (Time To Collision).

Decision tree: decision tree, data mining, Ordered Probit model.

Roads: roads, negative binomial, bike exposure, latent class model, predictive models, SPF (Safety Performance Function).

Traffic violations: traffic violations, vehicle-bike interaction.

Surrogate measures: surrogate measures, video analysis.

Traffic engineering computing: traffic engineering computing, roads & highways.

Lateral clearance: lateral clearance, three-foot rule.

Passing distance: passing distance.

Anger: anger, aggression.

Children: children, hazard perception.

AEB: AEB (Autonomous Emergency Braking), active safety, crash avoidance, trucks, crash warning.

Fig. 5. Thematic map by author keywords.

diagram is divided in four quadrants and, according to their position, the themes can be classified as follows (Rodrìguez-Soler et al., 2020; Aria et al., 2021):

1. Motor themes: characterized by high value of both centrality and density. Relevant topics mapped in this zone are widely and over a long period of time treated by a well-defined group of researchers.

2. Niche themes: defined by high density and low centrality. Clusters are strongly developed but still marginal for the research field.
3. Emerging or declining themes: featured by low value of both centrality and density. Themes are not fully developed or of limited importance for the research domain.
4. Basic themes: distinguished by high centrality and low density. Clusters are represented by basic and transversal themes relevant for the research field and transversal to its different areas.

A minimum threshold of 5 occurrences was imposed to filter only the most frequent keywords. Each cluster is labelled with the corresponding most frequent keywords and the dimension cluster is proportional to total occurrences of the keywords that compose it. Below thematic map, all keywords which compose each cluster were provided.

In **motor themes** crash severity and bike network were located. These clusters embodied driving topics which were well developed by researchers over time. A theme such as "overtaking" interposed between motor themes and basic themes was well developed and capable of structuring the research field. In other words, overtaking remained the leading theme within the field. Clusters composed by decision tree, driving simulator, bikeshare, e-bike, and helmet represented **basic themes** being very important for the field's development. Their high centrality and low density make them crucial and workable key themes for future research.

Niche themes involved anger, traffic engineering computing, anger, lateral clearance, passing distance and children. Niche themes stand for highly treated but still of marginal contribution to the development of the cyclist safety field. Thus, themes in the upper left quadrant are potential topics that need to be more connected to cyclist safety. Interestingly, AEB (Autonomous Emergency Braking) started to shift from a peripheral to a more central position, having a high density and a medium centrality level.

Finally, roads, surrogate measures and traffic violation could be **emerging or declining themes**.

Certainly, the motor themes related to crash severity and bike network deserve further investigation. Cyclists have much higher injury risk and fatality risk than car occupants (Nilsson et al., 2017) because, unlike cars, bicycles can easily become unbalanced and provide no protection in the event of a crash, allowing riders to come into direct contact with the road and other road users. The large amount of research dealing with crash severity highlights how this issue is becoming relevant for the scientific community. Thus, we carried out a deep analysis of the main methodological issues and the main crash severity contributory factors.

Cyclist injury severity is influenced by numerous factors that are related to roadway, environment, vehicle, driver, cyclist, and crash characteristics (see Table 6). Liu and Fan (2021) found different sets of factors that significantly impact cyclist crash severity on weekdays and weekends. The results showed that older cyclists, riding direction, pickup, older drivers, male drivers, and time periods 0:00–5:59 and 10:00–14:59 increase crash severity on weekdays, meanwhile speed limits of 45–55 mph, commercial development, head-on crash type, and non-roadway locations are significant contributory factors of higher crash severity on weekends. An additional distinction has been made between contributory factors at intersections and non-intersection locations (Lin and Fan, 2021) and between urban and rural areas (Lin and Fan, 2019). Cyclists drinking alcohol, vehicle type van, bus, or single-unit truck, motorists' fault, inclement weather, dusk or dawn were found to have a significant effect on cyclist injury severity at intersections. Cyclist gender, drivers drinking alcohol, vehicle speeding, curved roads were found to have a significant impact at non-intersection locations. Factors including cyclist age from 25 to 54, driver age under 25, vehicle speeding, and divided roads affect injury severity in bike-motor vehicle crashes in rural areas only. On the other hand, factors such as drivers age over 60, vehicle type van and single unit truck, head-on crash, motorist overtaking bicyclist, two-way roadway, road

Table 6
Crash severity contributing factors.

Variables	Contributory Factor	References
Roadway factors		
Speed limit	50–60 km/h	Isaksson-Hellman and Toreki, 2019; Wang et al., 2021
	≥70 km/h	Boufous et al., 2012; Kaplan et al., 2014
Area	Rural	Boufous et al., 2012; Hosseinpour et al., 2021
Road type	Motor vehicle lanes	Du et al., 2013; Wang et al., 2021
	Sidewalks	Gitelman and Korchatov, 2021; Wang et al., 2021
	Curves	Alshehri et al., 2020; Boufous et al., 2012
	Unlit roads	Boufous et al., 2012; Wang et al., 2015
Environmental factors		
Season	Summer	Hosseinpour et al., 2021; Ouni and Belloumi, 2018
Lighting	Dark	Boufous et al., 2012; Hosseinpour et al., 2021; Samerei et al., 2021
Pavement	Slippery road surface	Kaplan et al., 2014
	Wet road surface	Rash-ha Wahi et al., 2018; Wang et al., 2015
Weather	Foggy and rainy	Samerei et al., 2021; Wang et al., 2015
Vehicle factors		
Vehicle type	Motor-vehicles	Meredith et al., 2020; Seah et al., 2018
	Heavy goods vehicles	Damsere-Derry and Bawa, 2018; Joo et al., 2017; Kaplan et al., 2014; Chen and Shen, 2016
	Buses	Damsere-Derry and Bawa, 2018
Driver factors		
Behaviour	Speeding	Behnood and Mannering, 2017; Liu et al., 2020
	Driving on the wrong side of road	Behnood and Mannering, 2017
	Changing direction	Ouni and Belloumi, 2018
	Hazardous overtaking	Calvi et al., 2021; Lin and Fan, 2019; Ouni and Belloumi, 2018; Piccinini et al., 2018; Thomas et al., 2019;
Psychophysical state	Alcohol-impaired	Behnood and Mannering, 2017
Age	greater than 55	Wang et al., 2015
Cyclist factors		
Behaviour	Not wearing a helmet	Behnood and Mannering, 2017; Boufous et al., 2012; Marinovic et al., 2021; Samerei et al., 2021; Wang et al., 2021
	Windshield use during winter	Wang et al., 2021
	Red light violations	Bai and Sze, 2020; Du et al., 2013; Jahangiri et al., 2016; Wang et al., 2021; Wu et al., 2012
	Using cell phone when riding	Buhler et al., 2021; Du et al., 2013; Wang et al., 2021
	Speeding	Damsere-Derry and Bawa, 2018
	Riding on the wrong side of road	Behnood and Mannering, 2017; Hamann et al., 2015
Psychophysical state	Alcohol-impaired	Behnood and Mannering, 2017; Marinovic et al., 2021
	Intoxication	Kaplan et al., 2014; Liu et al., 2020
Gender	Male	Ouni and Belloumi, 2018; Hosseinpour et al., 2021; Meredith et al., 2020; Damsere-Derry and Bawa, 2018
Age	< 16	Kaplan et al., 2014; Oxley et al., 2016; Wang et al., 2015
	Older aged	

(*continued on next page*)

Table 6 (*continued*)

Variables	Contributory Factor	References
		Bahrololoom et al., 2020; Behnood and Mannering, 2017; Blaizot et al., 2013; Boufous et al., 2012; Chen and Shen, 2016; Kaplan et al., 2014; (Kroyer, 2015) Liu et al., 2020; Liu and Fan, 2021; Oikawa et al., 2019; Samerei et al., 2021; Wang et al., 2015; Weber et al., 2014
Crash factors		
Crash type	Two or more vehicles involved	Damsere-Derry and Bawa, 2018
	Head on crash	Boufous et al., 2012; Lin and Fan, 2019
	Cyclists going straight or turning left and other vehicles going straight	Kaplan et al., 2014
Injury type	Head injury	Brand et al., 2013; Oikawa et al., 2019
	Trunk injury	Seah et al., 2018

condition, and crash time are found to have a significant impact on the cyclist injury severity in urban areas only.

Usually, roundabouts increase capacity and reduce vehicle crashes, but some studies have found that the roundabouts increase the risk for cyclists. Akgun et al. (2018) examined which design factors affect cyclist crash severity at roundabouts. According to this study, the probability of a serious crash rises for each additional lane on approach and with a higher entry path radius.

From a methodological perspective, different approaches were used (see Table 7). Most studies used discrete outcome models treating injury severity as either a nominal or ordered variable, while other papers papers used machine learning approaches.

Table 7
Approaches used for crash severity analysis.

Models	References
Un-ordered discrete models	
Generalized additive model	Chen and Shen, 2016
Generalized linear model	Xing et al., 2020
Latent class cluster analysis	Sivasankaran and Balasubramanian, 2020; Samerei et al., 2021
Logit model	Akgun et al., 2018; Boufous et al., 2012; Ghomi et al., 2016; Kent et al., 2021; Lin and Fan, 2021; Samerei et al., 2021; Salon and Mcintyre, 2018; Wang et al., 2021
Negative binomial regression	Tuckel, 2021
Partial proportional odds logit model	Liu and Fan, 2021; Wang et al., 2015
Random parameter logit model	Bahrololoom et al., 2020; Behnood and Mannering, 2017; Lin and Fan, 2019; Lin and Fan, 2021; Wu et al., 2019a; Wu et al., 2019b
Spatial negative binomial model	Seah et al., 2018
Ordered discrete models	
Ordered logit model	Chen and Shen, 2016; Kaplan et al., 2014; Liu et al., 2020; Liu and Fan, 2021
Ordered probit model	Ghomi et al., 2016, Joo et al., 2017, Lin and Fan, 2021
Random parameters ordered probit model	(Fountas et al., 2021)
Geographically weighted ordinal logistic regression	Liu et al., 2020
Machine learning models	
Association rules	Anysz et al., 2021; Ghomi et al., 2016
Bayesian networks	Prati et al., 2017
C4.5 algorithm	Katanalp and Eren, 2020
CHAID decision tree	Prati et al., 2017
Classification and regression tree	Ghomi et al., 2016; Xing et al., 2020
Decision tree	Joo et al., 2017
Decision tree-based fuzzy logic model	Katanalp and Eren, 2020
Gradient boosting	Zhu, 2021

Different data mining techniques were used by Ghomi et al. (2016) to identify the main factors associated with injury severity of VRUs involved in crashes at Highway Railroad Grade Crossings (HRGCS). Ouni and Belloumi (2018) described the spatial pattern of VRUs crash according to different temporal scales such as (a.m. vs p.m. rush hours VRUs crashes, working days vs non-working days VRUs crashes, daytime vs night-time VRUs crashes) and investigated the influence of personal and environmental factors for VRUs injuries severity within the Centre-East region in Tunisia. Otte et al. (2012) developed a hierarchical system ACASS (Accident Causation Analysis with Seven Steps) in GIDAS, describing the human causation factors in a chronological sequence. The accordingly classified causation factors - derived from the systematic of the analysis of human accident causes ("7 steps") - can be used to describe the influence of the crash causes on the injury outcome.(Zhang et al., 2018) developed a cross-sectional study to interview 3,151 electric bike/moped riders in southern China to identify the prevalence and potential risk factors of electric bike/moped-related road traffic injuries among electric bike/moped riders. Zhu (2021) integrated imbalanced data resampling, learning-based feature extraction with gradient boosting algorithm and marginal effect analysis to determine the significant factors that contribute to the severity of vehicle-bicycle crashes based on the crash dataset of Victoria, Australia. Damsere-Derry and Bawa (2018) conducted a basic descriptive analysis to establish the injury severity and patterns among cyclists in Northern Ghana. Furthermore, several scholars performed retrospective studies for medical and technical analysis as a basis for preventive measures (Brand et al., 2013; Marinovic et al,2021; Savitsky et al., 2021; Siman-Tov et al., 2018; Zmora et al., 2019).

The second cluster located in the motor themes quadrant includes "bike network" topic. To promote the bike use, bike-friendly environments are essential (Joo et al., 2015; Teixeira et al., 2020). Safety matters are the major obstacle for enhancing the bike as a mode of transport due to the dangerous interactions with motorized vehicles. The separation of the cyclists from the motorists through separate cycling facilities is a common practice in uncongested traffic (Buehler and Pucher, 2012; Cicchino et al., 2020; Schepers et al., 2013; Teixeira et al., 2020). Nevertheless, on congested roads, implementing separate bike lanes faces resistance at times and is not easy to understand and digest for habitual road users who feel such designs do nothing more than reduce the vehicle-destined spaces (Montella et al., 2022). In this regard, Bagloee et al. (2016) employed a method to find latent misutilized capacity in the congested networks to be specialized for exclusive bicycle lanes. Furthermore, Osama and Sayed (2016) highlighted the beneficial effects of the bike network continuity on cyclist safety. Even though on primary roads the high rates of road crashes take place, they are usually preferred by cyclists (Arellana et al., 2020; Teixeira et al., 2020). The building of well-designed and safety bike networks has been identified as the most crucial factor for promoting citizen's mobility and accessibility as well as opposing the motorization effects. Lin and Yu (2013) proposed the first network design model for bikeways in literature in urban areas. The aim was to minimize the cyclist risk, comfort, service coverage for residents and minimize the bike network impact on existing traffic. Arellana et al. (2020) showed that the safety perception increases for cyclists by boosting accessible bike facilities. Ng et al. (2017) exanimated which types of bike infrastructure the cyclists perceive safest at un-signalised intersections. Cyclists felt safer using bike infrastructure where they had to give way to turning motorists at the intersection than using cycling infrastructure where they had the right of way. In this way, cyclists may choose when it is safe to cross the intersection instead of caring about turning motorists who could be trying to overtake them. Thus, motorists' behaviours and attitudes towards cyclists should be evaluated before designing and implementing bike infrastructure at intersections.

To realize a bike network with safety, consistency, and immediacy, demands characteristics of bike paths including bike traffic consideration and cyclist's route choice behavior necessitate to be evaluated precisely. The Olive method proposed by Suzuki et al., (2012) represents a way to do it accurately and easily. However, different income groups benefit from bike lane networks not equally. For example, Tucker and Manaugh (2018) examined whether the provided bike lane has been reasonable among neighborhoods in Rio de Janeiro and Curitiba. Both cities were found to have more than twice the bike lanes provisioning in the richest quintile than the lowest income quintile relative to area and population. Furthermore, richer neighborhoods were found to have more commercial zones accessible along safer cyclist routes.

Based on identified contributory factors of cyclist crash severity and bike network concerns, appropriate safety countermeasures have been proposed overtime to support policy makers and engineers in choosing cycling safety improvement strategies. The cyclist and driver speed as well as high speed limit are among the most relevant factors impacting the injury severity in cyclist-motor vehicle crashes. Isaksson Hellman et al., (2019) evaluated how speed limit reduction influenced the injury severity for cyclists by studying crashes occurring in urban areas with different speed limits. The results showed that, reducing the speed-limit from 50–60 km/h to 30–40 km/h the cyclist risk getting a MAIS 2+ (Maximum Abbreviated Injury Scale) injury decreased by 25 %. Thus, safety improvement strategies may consist of optimally lower posted speed limits on streets with both bikes and motor vehicles (Chen and Shen, 2016), implementing road diets/traffic calming methods (Rella Riccardi et al., 2022c; Wang et al., 2015), law enforcement prohibition of speeding (Joo et al., 2017). Several researchers highlighted the importance of improving the bike network to reduce hazards to VRUs. Improvement of cyclist safety may be achieved by building cycle paths and delimitating lanes to physically separate cyclists from the others road users (Damsere-Derry and Bawa, 2018; Samerei et al., 2021; Tuckel et al., 2014; Tuckel, 2021). As a separation, a "forgiving" curb to consider that people make mistakes should be designed. The sloped curb, therefore, represents the best practice compared to right angled curbs (Janssen et al., 2018). It's also necessary to invest equitable among different income neighborhoods in well-connected and continue cycling infrastructure (Tucker and Manaugh, 2018; Walter et al., 2013, Wang et al., 2016). Simple but very useful measures to improve the cyclist's safety consist of removing obstacles such as poles from the bike path, observing guidelines on the minimum width of bike paths given traffic volumes, enhancing sight distances at intersections, and traffic light control without conflicts between traffic flows (Davidse et al., 2019). Cyclist behaviour and visibility in darkness is a key safety concern. Dark lighting critically reduces both drivers and cyclist sight. Further, lighting with light emitting diodes (LEDs) ((Rella Riccardi et al., 2022b)), reflective clothing for cyclists can improve visibility during the night-time and on unlit roads.

Furthermore, the development of educational programs focused on child bicyclists, older bicyclists, and older drivers as well as the improvement of AEB, the use of bicyclist detection technology for vehicles will need to assure a downward in the cyclist crash severity. Measures against dangerous cycling or driver behavior such as driving under the influence of alcohol and riding without a helmet can result in a reduction of fatal and serious cyclist crashes. Most of the severe injuries involved the head (Brand et al., 2013). Thus, the helmet usage could result in severity reduction of head injury (Bahrololoom et al., 2020, Walter et al., 2013, Wang et al., 2015). Helmet campaigns should be launched to increase helmet awareness and use (Savitsky et al., 2021; Tuckel et al., 2014; Wang et al., 2015) or mandatory helmet legislation (Marinovic et al, 2021; Samerei et al., 2021; Walter et al., 2013).

5. Discussion and conclusions

Cyclist safety is a research field that is gaining increasing interest and attention, but still offers questions and challenges open to the scientific community. The aim of this study was to provide an exhaustive review of scientific publications in the cyclist safety field. For this purpose, Bibliometrix-R tool was used to analyse 1066 documents retrieved from WoS between 2012 and 2021. The study examined published sources and productive scholars by exposing their most influential contributions, presented institutions and countries most contributing to cyclist safety and explored countries open towards international collaborations. Finally, keywords analysis was carried out by showing current research themes and emerging research directions.

Publication in cyclist safety field growth has been rapid since the last 10 years, and it is anticipated to continue to rise. One hundred seventy-one different sources released on cyclist safety. Notably, Accident Analysis & Prevention led the production between 2012 and 2021, attaining the highest number of published documents. Moreover, as a result of a bibliometric and scientometric overview Zou et al. (2020) confirmed that in recent years Accident Analysis & Prevention is increasing the publications on VRUs, especially on child bicyclists. Sources analysis results could address scholars in the choice of more suitable journal for their research papers.

An analysis of influential articles published in the field showed that the 70 % of the twenty most-cited papers have been published in Accident Analysis and Prevention. Cyclists still represent one of the road user categories with the highest injury and fatality risks (Prati et al., 2017). The EU remarked in the 2021–2030 EU road safety policy framework its long-term strategic goal to get close to zero deaths and zero serious injuries by 2050 (Vision Zero) (European Commission, 2021a), and its medium-term goal to helve deaths and serious injuries by 2030. Identifying the factors that affect crash injury severity is an important step towards accomplishing these goals. However, although there has been a quite large number of research studying safety of bicyclists, comparatively few studies have investigated the factors influencing bicyclists' injury severities. The study carried out by Behnood and Mannering (2017) represents a starting point for cyclist crash and severity analysis.

In addition to crash severity, highly cited papers have tackled issues such as factors contributing to crash frequency, e-bike, risk factors, overtaking, surrogate safety measures, helmet use, and bike network.

Regarding authors' contributions, Haworth from Queensland University of Technology (Australia) and Sayed from University of British Columbia (Canada) published most papers while Abdel-Aty from University of Central Florida (US) was the most cited author.

As regards the institution, Monash University (Australia) was the more prolific by publishing the highest number of papers. Similarly, the US made a significant contribution becoming the most active country in the field of cycling safety in the decade 2012–2021. China, US and Australia produced several documents in which there is at least one co-author from a different country by contrast with Norway, Germany, and Italy. It could be essential to develop a denser collaboration network across different countries in order to create a more global impact on cyclist safety.

Keyword analysis showed that crash severity, bike network had been main topics in cyclist safety field. A theme such as "overtaking" positioned between motor themes and basic themes. Furthermore, thematic analysis revealed that understudied but relevant topics such as decision trees, driving simulator, bikeshare, e-bike, and helmet need to be deepened. Thus, more effort into researching these topics which remain promising for researchers is suggested. On the other hand, models as decision trees or more generally data mining models represent the last methodological frontier to explore cyclist crash data by searching for structures, commonalities, and hidden patterns or rules. The need for data mining models come from the mass of complicated data on cyclist crashes. In presence of large and complicated datasets, data-mining methods may be preferred to econometric models by requiring relatively short data preparation time and providing satisfiable accuracy (Mannering et al., 2020; Rella Riccardi et al., 2022a; Zhu, 2021). Moreover, data mining techniques such as decision trees can properly handle many discrete variables or variables with a high number of categories, have no problem with outliers and don't need a priori assumption on variable distributions, overcoming regression models limits in crash analysis (Prati et al., 2017).

The clusters labelled driving simulator encloses topics related to technological innovations such as driving simulators, automated vehicles, ITS, ADAS, and bike simulators. Most of bike facilities are due to crashes between motorized vehicles and cyclists. Active safety systems are a possible countermeasure able to support drivers in avoiding or mitigating collisions with VRUs. Examples of these active safety systems are some of the ADAS such as AEB, which promptly activates an autonomous braking in case of crash and the Forward Collision Warning, which triggers a warning to the driver in the event of a possible collision with a VRU. Furthermore, European parliament with the regulation 2019/2144 (European Commission, 2019) ordered that new vehicles registered from 2022 onwards must be equipped with specific ADAS to reduce road fatalities by minimizing human error. The latter necessitates a deep understanding of driver behaviour to be effective without being uncomfortable. Driving simulators are one of the main testing environments for studying driver response processes (Boda et al., 2018; Brijs et al., 2022), offering opportunities for safe and controlled traffic safety research. Indeed, driving simulators allow more people experiencing identically critical situations without risk of injuring themselves or others (Thorslund and Lindström, 2020). Also, aspects of cyclist behaviour can be investigated using the bike simulators. In recent years, ITS have proved their effectiveness reducing road fatalities by minimizing human error. However, most of the existing ITS safety applications are focused on vehicles, and hence the impacts and usability of ITS applications for VRUs require more research (Scholliers et al., 2017; Silla et al., 2017). The modern transportation is shifting from human-driven vehicles to semi-automated and, eventually, fully autonomous vehicles. In this prospective, the interaction between vehicles and cyclists will be a relevant issue. Currently, human perception, formal rules, social norms, and interpersonal interactions ore responsible for vehicle-VRUs Interaction. When vehicles will become more automated this interpersonal interaction must switch to a human–machine interaction (Owens et al., 2019). Thus, automated vehicles lay the foundation for technological and safety challenges. Due to the large increase in vehicles on the road over the years, cities are overwhelmed. Therefore, it's necessary to support micro-transportation modes (e.g., bike) and bike-sharing systems as environmentally friendly alternative to motorized vehicles. Bike-sharing systems show significant transportation, environment, and health benefits and allow to mitigate traffic jams (Almannaa et al., 2020). Moreover, e-bike sharing systems have been also introduced recently. E-bikes was become a popular travel mode for citizens. They are as convenient and flexible as conventional bicycles but can reach much higher speeds (30 km/h or even higher). However, limited regulation and lack of in-depth research about the risks involved in using these micro-mobility transportation modes raise numerous safety concerns. The e-bike growth has been particularly rapid but very little research has been conducted to assess the road safety implications. Safety is a critical factor in promoting sustainable urban non-motorized travel modes. Esmaeilikia et al. (2018) identified 28 countries around the world with a bicycle helmet legislation. Most countries apply legislation only to children below a certain age while only nine countries have bicycle helmet laws that apply to all ages (Argentina, Australia, Finland, Malta, Namibia, New Zealand, Nigeria, South Africa, and United Arab Emirates as well as half of Canadian provinces, some US cities, urban travel in Chile and Slovakia, and interurban travel in Israel and Spain). Several studies found that helmets reduce injury severity in bicycle crashes (European Commission, 2021b; Høye, 2018; Høye et al., 2020) but their effects on cyclist' behaviours still need deeper understanding, especially considering the increasing of shared bicycles (Kang et al., 2021).

Motor themes such as crash severity and bike network were further explored. Crash severity analysis is crucial for getting useful information regarding where the prevention should be targeted to plan, design, and manage a safer transport system. From a methodological perspective, both discrete outcome models and machine learning techniques were used. Among studies that implemented discrete outcome models some of them treat injury severity as a nominal variable and others as ordered variable. Several factors related to roadway, environment, vehicle, driver, cyclist, and crash characteristics are found to have a significant impact on the cyclist's injury severity. On the other hand, there is considerable evidence that cyclists' safety perceptions of bike network influence their desire to ride on existed bike infrastructure by having an important impact on the use of bike. The main finding related to well-designed and safety bike networks as well as to the equity issue for accessing appropriate bike lanes were discussed.

Based on the identified cyclist safety concerns, several engineering, social, and management adequate countermeasures are recommended.

A database constantly updated is the core of the study. As cyclist safety is an emergent issue, bibliometric analysis could substantially change in a few years. However, the research outcome will be useful to develop strategies for making bike a safer and more confident form of transport as well as to guide researchers towards the future scientific knowledge.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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