Key contributory factors influencing cycling safety: A comprehensive review based on accident data and literature survey

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Abstract

In the past years, it is evident that cycling is becoming an alternative transportation mode of driving and gains more popularity among all age groups particularly in metropolitan cities due to COVID-19. Although cycling is beneficial to individuals and urban cities (i.e., reduction of traffic congestion, and promotion of a healthy lifestyle), it could also expose cyclists to risky situations, resulting in serious consequences. Therefore, this research aims at conducting a comprehensive analysis of the key contributory factors by using the data derived from the cycling accident and literature reports. More specifically, the accident data is first used to prioritise contributory factors contributing to a high level of cycling risk, and then the result guide the development of the literature review. The literature review analysis is emphasised on the characteristics, relationships, and control measures against different selected contributory factors identified from cycling accident reports. The in-depth analysis aids to figure out and better understand what the characteristics and relationships of these factors are, how they affect the safety of cyclists individually and jointly, and what to do to control their negative effects. The findings will not only provide practical insights for transport authorities to control contributory factors influencing cycling safety, but also engage more research for the improvement of cycling popularity, prevention of cycling risks, and enhancement of cycling safety in future.

Keywords: *Review, Cycling risk, Cycling safety, Contributory factor, Risk matrix*

Introduction

Although it was deemed as a neglected and unvalued transportation mode in the past, cycling is gradually becoming a popular way for commute, transport, exercise, and recreation around the world nowadays. The popularity of cycling is stimulated by multiple reasons, such as the population of sharing bikes around the world (Eren & Uz, 2020), the expansion of bike commuting, and the increasing cycling propaganda in large cities due to the outbreak of COVID-19 to keep social distance and avoid crowded transport means (Americas Quarterly, 2020; Useche et al., 2021). Along with the safety concern of using public transport, it is not surprise to see the increase in popularity of cycling as it has been treated as an effective way to reduce traffic congestion and environmental pollution, promote a healthy lifestyle for public (Anderson et al., 2002; Higgins, 2005; Heinen et al., 2010), and bring other benefits to individual users, such as easing the burden of vehicle parking, exercising the body and reducing travel cost. According to the statistics presented by Oke et al. (2015), there are at least 580 million bicycles in the possession of the world's households in 2015, which means four out of ten households around the world have bicycles within their arm's reach, demonstrating cycling is one of the major travel mode choices for many families worldwide, especially in China and India who has higher percentage of bicycle ownership. Consequently, the growing popularity in transport cycling triggers the increasing interest of city councils in making urban transport infrastructure more bicycle friendly. For example, the pioneering country who has a well-developed cycling system, Netherlands, is enjoying benefits of their efforts. More than one-quarter of trips is by bicycle selected by Dutch residents, especially at big cities such as Utrecht (40%) and Amsterdam (35%) (Lucas Harms & Maarten Kansen, 2018).

Despite such benefits, safety of cycling is under debate due to the vulnerable nature of cyclists (i.e., Balakrishnan et al., 2019) and a broader age distribution from children to the elderly compared to the other types of road users. In many countries of mixed traffic systems, cyclists often have to share same infrastructures with cars, buses and trucks but are not protected like the motorized road users (Reynolds et al., 2009). In the UK, for instance, although cycling makes up a small number of the traffic on British roads (around 3% to 4%), it is a more vulnerable transportation mode compared to others (i.e., driving, motorcycling). According to the statistics provided by the UK Department for Transport, there are 167,375 vehicles involved in reported injury road collisions in 2021, and pedal cycles occupied 10.01%

of them (16766 of 167375). In addition, among 1114 casualties caused by road collisions, 12.66% (141 of 1114) of them are pedal cyclists. These figures indicate that cyclists are more likely to be injured in an accident, or to be killed in the UK on the road.

Taking the city of Liverpool for an example, the Liverpool City Council launched a 12-year ‘Liverpool Cycling Revolution’ plan in 2014 which aims to get at least 15% of the population cycling at least once a month by 2026. Thanks to this plan, the number of commuters by bicycle in Liverpool is growing fast annually, with 62% more journeys by bike in 2018 compared to 2006. However, unlike other cities in Europe where a well-developed cycling system exists such as Amsterdam and Copenhagen, cycling in UK cities also renders cyclists uniquely vulnerable to many risks, which are caused by risk factors such as infrastructure deficiencies, wrong maneuvers, and inclement weather. These adverse natures and conditions could expose cyclists in dangerous environments, given that casualty rates of pedal cyclists are almost 18 times higher than car drivers in 2021, which is rev ealed by Department for Transport in UK in their annual report 2021 of reported road casualties. The increasing casualties among cyclists per year stimulates the concern that the safety of cyclists when cycling needs to be reviewed and protected on an urgent basis. Hence, ensuring cycling safety could dispel the concerns on cycling safety among citizens, resulting in a higher cycling usage rate and environmentally friendly city.

Safety can be ensured through risk assessment, indicating higher priority should be given to factors of high risk and corresponding effective control measures to protect cycling safety. Regarding the research of cycling safety, a number of studies have been carried out in recent years with a focus on different segments of risk factors influencing cycling safety, such as the effect of cyclist behaviors to the crash rates and injury severity (Poulos et al. 2015), the risk factors associated with cyclist safety involving cycling infrastructure (Schepers et al., 2011; Mantuano et al., 2017), the analysis on crash and injury rates as well as the trends in a particular region (Tin et al., 2009), the contributory factors for cycling crashes (Prati et al., 2018) and other research orientations. Despite the large quantity of existing research, it is necessary to review and ensure the possible full contribution of these academic research on protecting and improving cycling safety in particularly concerned cities where both cycling traffic and accident rates rise. It is beneficial to introduce a new methodology in which both academic findings in research and accident reports in reality are both taken into account in a complementary and holistic way to analyze the role of contributory factors beyond the cyclists, road users, and road environments involved.

Within this context, this paper aims to conduct a comprehensive review on key contributory factors through an analysis on the risk data derived from all cycling related accident reports in a selected city region (i.e., Liverpool) of a fast-growing cycling accident rate. The literature review analysis is emphasised on characteristics, relationships, and control measures against the prioritised contributory factors that are identified from accident reports using a risk matrix approach. The in-depth analysis aids to figure out and better understand what characteristics and relationships of these factors are, how they affect the safety of cyclists individually and jointly, and what to do to control their negative effects. It will yield an archive of the recent literature on the studied topic and offer not only researchers with the information needed to support the continuity of the relevant research in the area, but also the transport authorities with suggestions in controlling key contributory factors and protecting cycling safety. In addition, research outcomes of the research will provide helpful insights and practical contributions to control contributory factors and protect cycling safety for both academics and practitioners in different regions under similar conditions.

The remaining part of this paper is organized as follows. Section 2 describes the review of the methodology applied to select relevant studies in all possible resources. It is followed by the identification of the key contributory factors through collected accident reports in Section 3 and the introduction of relevant studies reviewed in this research in terms of the distribution of basic information (i.e., years of publication, journals, and research methods) in Section 4. Characteristics of the factors and their relationships are presented in Section 5. Control measures for the key contributory factors from the relevant literature are summarized in Section 6 and conclusions are provided in the final section.

Methodology of review

Since the objective of this work is to offer both researchers and transport authorities with useful information and suggestions, a systematic literature survey procedure consisting of three parts for searching, selecting, and analyzing the relevant articles is applied to carry out a comprehensive review of cycling risk contributory factors: 1) identification of key contributory factors through investigating cycling accident reports, 2) relevant article selection and analysis based on the identified factors of high risk in the first part, and 3) comprehensive analysis on key contributory factors by the hybrid of accident report investigation and literature review.

There is a tight connection between these three parts. Through investigating accident reports, key contributory factors influencing the cycling safety in a particular concerned city region are clarified, which could help focus on those factors with significant risk effect and avoid a waste of time and resources for the sake of effective control on cycling safety, as there are lots of contributory factors influencing cycling safety and it is impossible to analyze each of them equally and require transport authorities to control selected prioritized factors from a practical perspective.

Based on the review on related works focusing on identified contributory factors from accident reports, the impacting mechanism of each factor is figured out and corresponding effective suggestions are summarized, aiming at providing useful insights and targeted measures for transport authorities to protect cycling safety effectively. In addition, an overview of relevant research in this field is also able to provide a clear recognition of this field and serve as a reference for other researchers who wants to conduct continuous studies. In general, the incorporation of three sections in the methodology together comprise the core content of this research, covering both the academic and practical contributions. The detailed description of each part is presented in the ensuing sections.

Investigation on accident reports

Accident reports used to identify contributory factors comes from the STATS19 accident report applied by the Department of Transport in the UK (DfT, 2011). It consists of a set of data that are collected by a police officer when a road accident is reported. Accident reports are used extensively for research work and for guidance in the improvement of road safety policies in relation to road, road users and vehicles.

In this paper, 2269 STATS19 reports involving cycling accidents in Liverpool from 2012-2017 are collected from Merseyside Police as the case data to help determine major contributory factors influencing cycling safety in the city region. Each report includes a great variety of characteristics related to the occurrence of cycling accident involving dozens of factors influencing the cycling safety, as seen in the official STATS19 form from UK DfT website (UK DfT STATS19 form, 2020).

Through the judgment and evaluation on different contributory factors using advanced approaches such as Bayesian networks (i.e., Yang et al., 2021) and a risk matrix approach (i.e., Ni et al., 2010), the importance degree of these factors (both individually and jointly) is clarified, which provides a reference for the selection of relevant research articles in the second part of the work (i.e., Section 2.2.).

Selection of reviewed articles

The procedure to select reviewed articles consist of two steps: (1) online database searching, (2) article screening and refining. It is to find the hidden information which could not be easily obtained from accident reports, including the characteristics of and control measures against prioritized factors. As a result, the finding can provide useful insights for cycling risk control measures against prioritized factors for the first time. The Web of Science (Core Collection) database, as one of the most comprehensive multidisciplinary content search platforms for academic research (Hosseini et al., 2016), is used to select relevant papers in this study. The combination of search strings applied as the topic to conduct the searching works are 'cycling-hazard', 'cycling-safety', 'cyclist-risk', 'cyclist-safety', and 'cyclist-risk analysis' within a time period from 2007 to 2022.

Following the initial search and removal of duplicates, a search of titles and abstracts from all retrieved paper was refined at the next stage based on the following screening process.

Step 1: Only peer-reviewed academic journals are selected for further analysis because peer-review process is the most guaranteed one for the acceptance of the scientific community (Bergström et al., 2015). It means that book chapters, papers written in other languages and lack of basic information are excluded.

Step 2: Full-text review is then conducted. Since this study focuses on the analysis of contributory factors influencing cycling safety, the articles that addressed the cycling safety from other perspectives are excluded, including papers whose topics are about crash, injury, as well as those topics are injury severity and medical care for cyclists. Besides, the articles that only treat contributory factors in cycling as subtopics or as a label are excluded, i.e., advanced techniques, devices, or equipment in cycling, or for an education purpose.

Step 3: In the last step, the retained papers are further refined based on the key contributory factors identified from Section 2.1. Only those papers relating to the relevant topics are taken into consideration in this paper.

For each of selected academic journal papers, the following information is extracted:

- the publication year and the published journals
- the investigated geographical area(s)
- the applied research method(s)
- the involved contributory factors influencing cycling safety

Comprehensive analysis on contributory factors

To achieve the objective of our research and alleviate the impact brought by these contributory factors, a comprehensive analysis consisting of three parts is conducted based on the selected literature:

1) Characteristics of these key contributory factors and their influence on cycling safety
2) Relationships between different contributory factors identified from the literature
3) Control measures proposed in the relevant studies to alleviate the impact of factors

The detailed analysis is presented in Sections 5 and 6.

Identification of key contributory factors based on accident data by a risk matrix approach

The STATS19 report is analyzed nationally by reference to a great variety of characteristics and attendant circumstances, and the results are used extensively for research work and for guidance in the improvement of road safety in relation to roads, road users, vehicles, and traffic movement in UK.

All road accidents involving human death or personal injury occurring on the highway and notified to the police within 30 days of occurrence, and in which one or more vehicles are involved, are to be reported.

It is worth noting that the STATS19 report takes the accidents involving pedal cycles into consideration, which is a great improvement compared with the practice in the past. In the past the interpretation of "mechanically propelled vehicle" has varied widely between local police forces, particularly about whether pedal cycle accidents, not involving a motor vehicle, should be reported. The requirement of a

STATS19 report is clear that all accidents involving non-motor vehicles such as pedal cycles on 'public roads' should be reported, regardless of motor vehicle or pedestrian involvement.

In a STATS19 report, there is an important component called ‘contributory factors’, which are key actions and failures that led directly to the actual impact. It reflects the reporting officer’s opinion at the time of reporting. In each accident, the police officer should give an indication of which contributory factors in the handbook contribute to the accident, with an upper limit of six relevant factors for the selection. Therefore, contributory factors are selected depending on the knowledge and experience of the investigated officer to reconstruct the events that directly lead to the accident. The reliability of the reports is assured by two measures: first, the contributory factors for an accident have to be identified based on the evidence rather than subjective judgments of officers on duty; secondly, each police officer is in charge of their own distributed areas, ensuring they are familiar with the area and gain useful experience on the occurrence of an accident in the field. These factors are defined from STATS20 handbook issued by the UK Department for Transport (UK DfT STATS20, 2020).

In total, there are 78 contributory factors in the handbook. Against the same factor, an accident is reported from two different perspective of the involving users as suggested by the STATS20 handbook: victim and the encountering road users. No matter the accident is caused by which sides, contributory factors recorded in the accident report values. Specifically, in the paper, the 78 contributory factors are classified and refined through 2269 obtained accident reports in the Liverpool city region to eliminate the insignificant factors in the city region by using a risk matrix approach and the results from a systematic study on the accident report-driven factor identification in the region (Yang et al., 2021).

The principle of a risk matrix approach is that risk is defined as a combination of severity of the consequences occurring in a certain accident scenario and its probability (Markowski & Mannan, 2008). That means the risk matrix consists of three elements: two input variables (severity of the consequences and its probability), and one output risk index, which are divided into different levels with qualitative descriptions and scales.

- Probability: The estimated occurrence probability of each contributory factor, denoted as P. In this research, frequency of occurrence is used as an operable substitute of probability.

- Severity: The estimated impact of each contributory factor to the cyclist(s) safety when an accident occurs, denoted as $R_{severity}$. In an accident, the severity of casualty is classified into three types according to the STATS19 report: ‘Fatal’, ‘Serious’, and ‘Slight’. A 'Fatal' includes only those cases where death occurs in less than 30 days as a result of an accident, a ‘Serious’ injury includes those cases like broken neck/back, severe head/chest injury, loss of body part, while a ‘Slight’ injury refers to those mild cases like pain, sprains, strains and bruising. For a contributory factor, it may lead to different accident types under different situations, which means a rational evaluation of $R_{severity}$ should consider the occurrence of all possible casualty types (i.e., fatal, serious, or slight) brought by each contributory factor.

  To achieve this objective, a concept called Severity Point (SP) is introduced in this research reflecting the level of $R_{severity}$. It is a comprehensive evaluation considering all casualty types and their corresponding occurrence probability, which is calculated by Eq. (1):

$$SP_i = \sum_{j=1}^{3} R_{ij} * C_j \qquad (1)$$

  Where SP_i is the *SP* of the *ith* contributory factor, *j* represents different severity types of accident (i.e., fatal, serious, slight), R_{ij} refers to the proportion of the *ith* contributory factor leading to *jth* severity types of accident according to the accident statistics, *Cj* is the assigned value of different severity types (i.e., C_{slight}=1, $C_{serious}$=10, C_{fatal}=100, because of the casualty loss gap between different types). For each contributory factor, the larger its SP is, the higher severity level it is assigned.

  Table 1 illustrates different levels of *Severity* and *Probability* based on the obtained accident data occurred in the Liverpool city region.

- *Risk index:* The assessment result generated by two key elements: Severity and Probability. With the probability and severity being classified as shown in Table 1, an original risk matrix consists of 25 cells and four shaped zones indicating different levels of *Risk index* is proposed (Ni et al., 2010), as shown in Fig. 1.

  Based on the risk matrix provided above, contributory factors are screened and refined based on the following filtering rules:

1) The occurrence number of contributory factors is counted and used for the calculation of the frequency and proportion distribution.
2) If a factor appears more than one time in an accident (i.e., both for victims and encountering road users), it will only be recorded once.
3) Contributory factors with similar meanings will be merged into a new category to avoid information redundancy and promote research visibility and easiness, resulting in 13 new categories.
4) Different contributory factor categories will be given different risk index levels corresponding to the zones they are located according to their probabilities and severity levels.
5) Categories with 'VH' and 'H' risk index levels are selected for further review and analysis work.

Consequently, four major categories are selected and illustrated in Table 2, along with a simple description. The selection procedure involving the risk index of different factory categories can be found in Table 3.

Additionally, the factors involved in these categories are presented in Fig. 2 based on their appearance in the derived accident reports, which are evaluated as key contributory factors in this research.

Detailed descriptions and explanations are illustrated in the following Table 4:

Systematic review of the papers on the identified key contributory factors

Focusing on the key contributory factors identified in Section 3, the relevant papers are collected and screened following the screening process designed in Section 2.2. The distribution of the literature by years of publication, journals, geographical areas, and research methods are generated in this section to have a fundamental understanding of the research work development in this field first before their in-depth analysis in Sections 5 and 6.

Full-text selection

The initial search yielded an original database containing 2519 records, with 2166 retained by following duplicate removal. Through a careful reading on titles and abstracts, 187 articles were selected. The number was decreased from 187 to 147 after picking up the peer-reviewed journals only according to step 1 of the screening process. Furthermore, 45 were removed as they did not meet the criteria of step 2. In the last step, only articles focusing on the identified factors are chosen, resulting in a database of 81 peer-reviewed academic journal papers. The detailed process is illustrated in Fig. 3.

Distribution by year of publication

The distribution of selected journal articles by year from 2007 to 2022 is presented in Fig. 4. Although a small exception in 2017-2019, the popularity of research focusing on these identified factors shows an increasing trend in recent years. It triggers a new finding that the peak in 2021 is consistent with the developments of bike-sharing and increasing cycling practice in the post of COVID-19. Given the long-lasting impact of COVID-19 on travel behavior (i.e., Skoczynski, 2021), studies on cycling safety will be crucial and attract increasing attention to prevent the occurrence of associated accidents.

Distribution by journals

Table 5 illustrates journals associated with selected articles in this research. Only journals with more than two publications are listed in this table. *Accident analysis and prevention* is undoubtedly the most preferred choice for publication, contributing to almost half of articles. *Transportation Research Part F* is another significant source. Other journals like *Journal of Transport & Health, Journal of Transportation Safety & Security, Sustainability, Journal of Safety Research, Safety Science, Transport Reviews* are also major sources for publications. It is not surprised to find that most of the research are closely connected with transportation, safety, and risk areas.

Furthermore, for the two preferred journals, *Accident analysis and prevention (AAP)* and *Transportation Research Part F (TRF)*, articles published on them show great diversity in many perspectives.

1) Major method type. It can be found that mathematical modelling, especially a regression model, is the dominant research method, accounting for 66.7% (26/39) of selected works published on *AAP* in our study, while the ones on *TRF* are totally different, which is more quantitative and statistical as 55.5% (5/9) articles selected a basic statistical analysis approach.

2) Variety of method types. In spite of the dominating role of modelling in *AAP*, publications on *AAP* cover a wider range of methods than *TRF*, for example, a Bayesian approach, review, advanced statistical analysis are among the methods that have been adopted on *AAP* rather than *TRF*.

3) Data source. Due to different dominating method types, data derived for studies published on two journals presents significant differences. Questionnaire or survey are major sources for collected data in *TRF* (66.7%), probably because basic statistical analysis is less accommodative to subjective data. On

the contrary, over 60% studies published on *AAP* were conducted based on accident reports or real-time cycling data, indicating a preference of objective data in *AAP*.

Distribution by geographical areas

The geographical distribution of the research could on one hand reveal in which areas researchers care more about cycling safety, on the other hand indicate safety concerns which are highly associated with the popularity of cycling in different countries or regions. Fig. 5 illustrates the geographical information of the relevant articles through Google Earth, where highlighting the occurrence number of corresponding regions. It is found that cycling accidents in Western European region (i.e., Netherlands, Germany, Denmark, UK), North American region (i.e., US, Canada), and Australia cover the majority of the research. Netherlands, US, Australia, Canada, Germany, Denmark, the UK are among the countries attracting more attention, which comply with the popularity of cycling, advanced cycling system or large number of cycling populations in these areas.

Furthermore, Table 6 shows the ratio between the cycling safety studies and percentage of cycling population in the named countries. It provides useful insights from two perspectives: On the one hand, it reveals the relevant research demand and supply for the first time, demonstrating new potential for research interest growth in terms of geography. Ratios of the UK and US are remarkably higher than other countries, indicating cycling situations in these two countries attract more research interests.

On the other hand, the ratio can be viewed as an index evaluating the safety performance of cycling systems in these countries. Countries with a lower ratio are more likely to have a safer and advanced cycling system, i.e., Denmark, Netherlands, and Germany, because less concern/research demand are placed on cycling safety from an academic perspective under a relatively high cycling preference. Instead, cycling systems in the UK and US are possibly less cycling-friendly and need to be further improved.

Distribution by research methods

The research methods applied to analyze the data in these studies can be classified into the following types: regression models (i.e., logit model, logistic regression, Poisson regression, linear regression, negative binomial model), basic statistical analysis (basic statistical tools and indicators such as count, percentage, S.D.), other advanced statistical analysis (i.e., ANOVA, Bivariate analysis), review, a Bayesian approach and qualitative analysis.

From Fig. 6, it can be seen that regression models are the dominant research method, accounting for over half of the selected articles (56.79%). As a popular tool to analyze the dependency between dependent and interdependent variables, the regression models are effective in clarifying the influence of different contributory factors on cycling safety, providing that the data is derived from accident reports, official cycling database, real-time cycling data, or questionnaires. Besides, basic statistical analysis (13.58%), review (13.58%), and other advanced statistical analysis (9.88%) are also preferred methods in this area. Their main advantages and disadvantages indicating their applicability in cycling safety area are summarized in Table 7 based on the obtained articles in this research.

Besides, there are always various challenges with collecting empirical data for Human Reliability analysis (HRA) in academic field (Laumann et al., 2020), and analysis on key contributory factors influencing cycling safety is no exception. Although simulated scenarios, real-time data and accident reports are able to increase the transparency about the uncertainties and provide objective assessment (Morais et al., 2020; Yang et al., 2018) in academic research, questionnaire, interview and other form of qualitative data can also work well in this field if the data is collected systematically and transparently.

In-depth analysis on key contributory factors

Characteristics for key contributory factors

Environment & Circumstance issues

Environment is defined by the World Health Organization (WHO) as the physical, natural, and social context in which the individual spends his or her time. It is known to be one of the important factors contributing to cycling safety (Davison & Lawson, 2006). Cycling under a comfort environment could effectively reduce the exposure of cyclists in risky situations (Dai & Dadashova, 2021). Both natural and social environment are analyzed and discussed as follows, with the physical environment (i.e., road surface condition, road environment) excluded by risk matrix screening as it is separated as a single contributory factor in the STATS20 booklet.

Darkness

Darkness (also presented as *night riding or road lighting issue*) has long been considered as one of the most dangerous contributory factors affecting cyclists' safety (Twisk & Reurings, 2013). It will greatly affect the visibility and conspicuity of cyclists, which on one hand weakens their ability to detect potential hazards in the environment, and on the other hand makes them hard to be found and noticed by other road users, thus increasing the risk to be involved in collisions and accidents (Bacchieri et al., 2010; Wood et al., 2013). Further, due to the reduced reaction time and ability to take an evasive action caused by the poor lighting conditions in the dark, cyclists are more likely to suffer severe consequences (Kim et al., 2007; Wanvik, 2009; Boufous et al., 2012), indicating darkness is indeed a contributory factor that would expose cyclists in huge danger.

Rural or Urban areas

There is always a debate on the cycling safety in rural areas or urban areas. Some researchers believed when comparing to urban areas, rural areas provide a safer environment for cyclists. They pointed out that most of the cycling accidents occurred in urban agglomeration and city center, rather than in suburb areas (de Geus et al., 2012; Dai & Dadashova, 2021). Higher chance of encountering conflicts in the daily mobility between cyclists and other road users, as well as higher speed limit for main roads and highways in urban areas, make rural areas a safer choice (Jaber et al., 2021).

However, other researchers disagreed with this viewpoint. Although the traffic density is high in urban areas, an advanced transportation system will constrain the negative effects brought by crowded traffic, and cyclists will be more careful and mannered under strict enforcement of traffic rules, thus improving their perception of cycling safety significantly (Lawson et al., 2015; Engbers et al., 2018; Hosseinpour et al., 2021). Instead, since bicycle usage is typically higher on urban areas than rural areas, car drivers in rural areas will have a conventional thinking that they have a lower chance to collide with cyclists, resulting in some unfortunate tragedies (Prati et al., 2017). Incomplete transportation system, lack of specialized facilities, unruly behaviors, as well as time delays for emergencies are other reasons that could increase the risk of cyclists being caught in an accident in rural areas (Boufous et al., 2012).

In fact, one possible reason for opposite views on which area is safer could be attributed to involved countries or regions of different research, as the influence of rural or urban areas would be largely affected by the specific nation conditions. Because of the diversities in the environment, policy, infrastructure, cycling popularity and other aspects, it is not surprised to see they reach different conclusions on the same contributory factor.

Inclement weather

Inclement weather refers to bad weather conditions at the time and location of an accident, such as rain, snow, fog, mist, and heavy wind. It is significantly associated with the occurrence of cycling accidents, as proved by many researchers (Ibrahim et al., 2021; Salmon et al., 2022). A convincing explanation for the effect of inclement weather is the reductions in visibility, traction, and reaction time (Kim et al., 2007; Prati et al., 2017). Cyclists and drivers will be distracted and affected under such situations and may not execute a rational or timely maneuver, i.e., brake, swerve. Additionally, road condition will become terrible under inclement weather (i.e., wet, slippery, icy, frozen), leading to more severe accidents due to greater impact speeds and worse impact angles (Kim et al., 2007). Despite there is another voice that cyclists and drivers are travelling with extra caution in adverse weather conditions (Robartes & Chen, 2017), the accident statistics witnesses cycling in inclement weather fosters more dangers on cyclists.

Obscured vision

No matter for cyclists or drivers, visibility is of crucially important for their safety, as suggested in previous studies (Wood et al., 2009; Dozza & Werneke, 2014). However, because of many unexpected things (i.e., inclement weather, trees, buildings, parked vehicles, dazzling headlights or sun, blind spots, road signs), the vision of cyclists or drivers will sometimes be obscured, preventing them from foreseeing a hazard (i.e., an approaching vehicle or a pedestrian in the road). It appears that they could have avoided it if they had been able to see it clearly. As pointed out by Boufous et al. (2012), the reaction time for both cyclists and drivers would be affected a lot if their visibility is compromised and obscured. Specifically, the risk of colliding with other road users increases twelvefold under such conditions (Madsen et al., 2013), indicating the terrible consequences caused by this contributory factor.

Judgment errors

When cycling on the road, cyclists/drivers need to make decisions under different scenarios based on their judgment, i.e., what is the rational distance they should keep away from other road users, which direction they should look at, whether the vehicle speed exceeds the warning level. If an error occurs during this judgment process, the safety of cyclists will be threatened.

There are lots of different types of judgment errors, for example, junction overshoot (a driver/rider who does not stop at a junction and overshot the stop line or give way markings) or restart (a driver/rider who has successfully stopped or slowed to give way at a junction, but has then moved off), failed to signal or misleading signal, failed to look properly, and failed to judge the path or speed), conventional and habitual judgment of other driver/cyclists' actions (McCarthy, 2022) which covers many aspects related to cyclist safety. Methorst et al. (2017) found that driver's scanning strategies at intersections or roundabouts will be greatly affected by their judgment. Many accidents occurred because of the failure of drivers to see cyclists approaching. Similar conclusions were found in Boufous et al. (2012). Besides, Prati et al (2017) have pointed out that the misjudgment of the time and speed of other road users may lead to the potential collision as well.

Nevertheless, besides the abovementioned studies, there is hardly any other research focusing on this topic. A possible explanation is that these judgment errors are normally consequential actions caused by other contributory factors, especially the behavior and status of road users. For example, the impairment or distraction may lead to junction restart or overshoot. This statement is verified in the STATS20 booklet, 'judgment error: wherever possible, further codes should be used to explain why these actions were taken'. Therefore, it explains the scarcity of research on this category.

Infrastructure issues

Because of the vulnerability comparing to motorized vehicle drivers, cyclists need to be given extra protection by transport authorities. In many countries like Netherlands, Denmark, and Germany, specialized cycling infrastructure and facilities have always been a focus of policy to protect cycling safety (Pucher & Buehler, 2008). Lack of related cycling infrastructure and facilities will pose threats to the safety of cyclists, as illustrated in many related studies (Pucher et al., 2011; Marquésa & Hernández-Herradorb, 2017; Li et al., 2017; Ryerson et al., 2021; Sanchez et al., 2022a).

Lacking or inadequate specialized cycling infrastructure

Transport for London 2008 have pointed out that cyclists reported fear of injury from lack of specialized cycling infrastructure, i.e., segregated cycling routes. The homogeneity principle suggests that cyclists should be separated from motorized traffic along distributor roads because the speed on motorized road exceeds 30km/h, which could bring potential safety hazards to cyclists. The presence of the homogeneity principle is normally viewed as the original explanation for the desirability of constructing separated or specialized cycling infrastructure (Schepers et al., 2017).

The benefits of cycling infrastructure have been discussed in numerous studies. It is found beneficial to greatly reduce the occurrence probability and severity of cycling-related collisions on the road, as proved by many studies focusing on different countries and regions (Schleinitz et al., 2015; Pokorny & Pitera, 2019; van Petegem et al., 2021). Therefore, it is evident that the cycling accident rate and injury severity are relatively low in the countries or regions with established and improved cycling infrastructure (i.e., Netherlands, Denmark). Further, it effectively demonstrates that the investment on specialized cycling infrastructure is valuable (Kaplan & Prato, 2015). The existence of specialized cycling infrastructure or a bicycle sharing system could further increase the perception that inherently encourages more people to cycle, as well as promote the priority of commuters and travelers when having long distance journeys (Prato et al., 2016; Sanchez et al., 2022b).

Different types of specialized cycling infrastructure

Generally, there are two forms of cycling infrastructures: Firstly, infrastructure that manages the road space for shared use by both motor vehicles and cyclists, i.e., cycle lanes within the carriageway; Secondly, infrastructure that separates cycle traffic from motorized traffic; Different types of cycling infrastructure under various situations have revealed diversified effects on cycling safety (Hels & Orozova-Bekkevold, 2007; Schepers et al., 2011; Saad et al., 2019; Aldred et al., 2021).

Shared paths are a popular type of cycling infrastructure worldwide because of its space saving design, i.e., main roads or roundabouts with cycle lanes. However, the safety of cyclists seems cannot be guaranteed on shared paths. According to the relevant studies, a high proportion of collisions involving cyclists happened on shared paths because of the large volume of traffic and the large number of intersections (Poulos et al., 2015). The core of keeping cycling safety on shared paths is to separate different user types, control the speed and the number of obstacles, as well as keep the road surface clean, as suggested by the research on the areas with good performance of shared paths (de Geus et al., 2012).

Separated cycle paths present a much better option than shared paths. There are a large number of studies comparing to the safety effect between separated cycle paths and on-roadway cycle paths in different locations, i.e., intersections (Strauss et al., 2015), roundabouts (Poudel & Singleton, 2021), main roads. The results proved the superiority of separated cycle paths over on-roadway cycle paths without exception. This is mainly because the separated cycle paths provide a cyclist-friendly environment and keep cyclists away from motorized traffic, thus reducing possible risks of encountering collision and suffering injuries.

It is effective to have bicycle crossings at intersections in terms of reducing the number of bicycle collisions. The reason is twofold: one is drivers approaching the crossing will decrease their speed and improve their field of view, while the other is cyclists will be more careful and cautious at bicycle crossings. However, when it comes to a two-way bicycle crossing, things are different due to the visual scanning problem of right-turning drivers, as disclosed by Schepers et al., (2011).

Behaviours and status of cyclists/drivers

Nowadays, errors caused by subjective human behaviors and person-related functions (i.e., fatigue, distraction, inattention, cognitive biases, and poor decision making) are primary reasons for accidents in many industries and fields (Ahmed & Demirel, 2020; Taylor, 2020), without exception for cycling safety. As indicated in the risk matrix analysis, behaviors and status of cyclists have both a higher level of probability and severity, which conforms to the reality that a large proportion of cycle-related crashes and accidents are consequences of inappropriate cyclist behaviors nowadays. Hence, the hazards arisen from an inappropriate cyclist behavior and personal characteristics are deserved to be paid more attention.

Drunk/Alcohol

There is an increasing trend in the use of alcohol breath test by the police to detect the drunk driving on the road around the world, as alcohol has been widely recognized as one of the most common and serious factors leading to road collisions (i.e., Bil et al., 2010; Huemer, 2018). However, although the alcohol breath test aims at finding out the illegal drivers offending alcohol-related regulations, the alcohol consumption of cyclists also plays an equally important role in leading to terrible cycling collisions. This is probably due to an alcohol-induced loss of attention, lucidity, and stability, which makes the cyclist dangerous to both himself and other road users (Orsi et al., 2014). In addition, the intoxicated cyclist's ability to detect dangers, react to unexpected cases and execute evasive actions are all greatly impaired, resulting in the increase in both the probability and severity of an accident (Kim et al., 2007). It is found that intoxicated cyclists have a greater risk to be caught in a fatal injury or an incapacitating injury (Robartes & Chen, 2017; Macioszek & Grana, 2022), such as severe head injury, broken neck or back.

It is noteworthy that the alcohol use among youngsters is experiencing an upward trend, which may lead to tragedies as youngsters tend to have a weak awareness of safety (Twisk & Reurings, 2013).

Distracted events

There are many types of distracted events hindering the performance of cyclists on the road, i.e., using mobile phones, listening to the music, attending to child in distress, eating or drinking, reading advertisement hoarding, an accident on the opposite carriageway. Among these events, the most discussed one in the literature is the use of electronic devices, highlighting its dominant and irreplaceable role in our daily life, as well as its huge negative effect on cyclist's safety.

Although using electronic devices (i.e., talking on the phone, listening to the music, wearing earbuds) are not causally linked to collisions or accidents, it can precede unintentional risky behaviors leading to cycling collisions (Useche et al., 2019). For example, wrong turn at intersections and failure to see other vehicles are counted relevant. According to the accident reports, the cyclists who use electronic devices frequently on the road are more likely to disobey traffic rules (Stelling-Konczak et al., 2017) and conduct irrational judgments. In other words, distraction caused by using electronic devices represents a threat for cycling safety because of their close relationship with other contributory factors (Useche et al., 2018).

Inexperience/lack of skill

Inexperience, or lack of skill, is usually connected with children or young cyclists (Martínez-Ruiz et al., 2014), as they either just learn how to ride, or fail to know how to deal with emergencies. Inexperience has a greater impact on serious collisions (Heesch et al., 2011; Twisk et al., 2018), mainly because of features of these young cyclists: Panic, hurry, confusion, precipitance, over confidence and most importantly, the weak awareness of safety. When encountering unexpected situations on the road, an inexperienced cyclist will perform irrational and dangerous actions, such as ignoring stop signs, red light violation, wrong turn, and irrational lane changing (Prati et al., 2017). Further, the exposure of inexperience cyclists in motorized traffic or high traffic density environment will lead to the increase of their fear of cycling, making them more vulnerable to be involved in cycling accidents. Therefore, it is of great importance to construct specialized cycle infrastructure if permitted, along with proper education.

High vehicle speed

High vehicle speed or exceeding a speed limit contribute to the increase in both the probability and the consequence of potential cycling accidents (Kim et al., 2007, Boufous et al., 2012). Related research has found that with the increase in vehicle speed, injury severity and accident probability will increase synchronously. Kaplan et al. (2014) concluded that speed limits of 50–60 km/h are associated with an increase of 17–32% of severe cyclist injuries and 21–45% of cyclist fatalities. Such increase is far more pronounced for speed limits above 70 km/h, with 32–54% higher probability of severe cyclist injuries and 274–326% higher probability of cyclist fatalities. A widely accepted explanation is that drivers tend to shift their eyesight to farther distances at high vehicle speed, resulting in a lower perception on their immediate surroundings (Macioszek & Grana, 2022).

Riding style/characteristics of cyclists

Everyone has his/her own characteristics, which will reflected in his/her riding style on the road, contributing to different levels of risk perception ability. A representative example would be the comparison between young and old cyclists. For young cyclists, they have fast response time, better eyesight, and health, but at the same time they are impatient, reckless, competitive, and aggressive (Wang et al., 2020). They seek strong sensations to raise their sense of existence, i.e., racing and chasing, zigzagging. Instead, old cyclists tend to have long reaction time, poor eyesight, and diminished risk perception, but they are careful and disciplined (Macioszek & Grana, 2022). They are risk-aversion cyclists and prefer to exhibiting more cautious behaviors (Poulos et al., 2015). Consequently, young cyclists are more likely to be caught in cycling accidents and serious injuries, as stated in many research and statistical data, because of their characteristics and pattern of riding. Another example is the different styles of male and female cyclists. Female road users were observed to perform mandatory and legal maneuvers (i.e., lane-changing) more safely compared to male road users in the connected environment (Ali et al., 2021).

Traffic rules violation

The fundamental objective of formulating traffic rules is to regularize the behaviors of road users, thus ensuring the safety of road users. Violation of traffic rules implies the explicit intention to ignore traffic rules, which will expose cyclists in danger (Wang et al., 2020). It is estimated that cyclists who stop completely at traffic signals are 40% less likely to be involved in crashes compared to those who do not comply the rules (Robartes & Chen, 2018). In spite of the various motivation for risky behaviors of cyclists, primary reasons are explained from two perspectives. First, the fluke mind and the influence of other cyclists. People generally believe that other's interpretations of an ambiguous thing are more likely to be accurate and will help them as a reference for their actions (Fraboni et al., 2016). That is to say, cyclists are prone to obey the traffic rules if they see a law-obeying cyclist, otherwise they may violate traffic rules with a fluke mind not being caught by police officers as lucky as others. Secondly, it is associated with the dissatisfaction with the traffic rules. Many cyclists being interviewed demonstrated that they were not satisfied with the traffic rules as they are primarily designed and planned for vehicle drivers or pedestrians, and declared they need to be given more protection by the related rules (Kummeneje & Rundmo, 2020). The dissatisfaction towards traffic rules breeds a violation action. In some cases, the existence of pavement markings would decrease the frequencies of relevant behaviors (Ohlms & Kweon, 2018).

Description of the relationships between key contributory factors

It is essentially to analyse relationships among different contributory factors because the joint effect of multiple factors could be much larger than the sum of the effects from each factor individually. In this paper, we define the relationship between any of two relevant factors by a connection link in a figure (i.e., Fig. 7). The relationship is formulated if one of the collected articles analyses the relationship between two contributory factors either qualitatively or quantitatively. Relationships are added in the contributory factor framework (Fig. 2) through undirected edges between factors with associated relevance.

Relationships between key contributory factors are described in Fig. 7. The edges can be identified through the following principle: start from one factor, then change the direction if there are curve corners, and end at the factor it meets. The edges identified from this principle indicates there exists a relationship between the start factor and the ending factor.

From Fig. 7, several new findings are obtained, including:

1) Behavior and status of cyclists/drivers is the contributory factor category that has the most relevance with other type of contributory factors, indicating behaviors and status of road users are easily affected by other factors (i.e., darkness, inclement weather, missing infrastructure), or are causes of other subsequent actions (i.e., traffic rules violation, judgment errors). Among these factors, riding style/characteristics of cyclists is the factor with the closest relationships, demonstrating the crucial importance and necessity of regulating and educating the cyclists to cycle with reasonable patterns (i.e., low speed, cautious riding, obeying traffic rules, increased risk perception). In addition, the relationships involving traffic rules violation are discussed more frequently in previous studies, probably due to that traffic rules violation is more likely a consequential action of corresponding behaviors or environments.

2) An infrastructure issue has relatively weak connection with other contributory factors, according to the number of relationships presented in Fig. 7. This phenomenon demonstrates that the infrastructure issue tends to be a more direct cause for increasing cycling risks, no matter the behavior and the judgment of cyclists, or the surrounding environments.

3) More relationships are found between behaviors/status of cyclists/drivers and judgment errors, highlighting the close relationship between these two contributory factor categories. Judgment errors are usually the results of negative behaviors or adverse conditions of road users, as mentioned in Section 5.1.2.

4) Relationships involving 'riding style/characteristics of cyclists', 'traffic rules violation', 'failed to see other vehicles' are among the most discussed and analyzed factors, which means they should be given extra attention by transport authorities for effective control measures.

5) There is hardly any research attempting to figure out the relationship between traffic rules/infrastructure issues and judgment errors. This is arguably an important area to understand the causation of cycling accidents comprehensively, which could be a research topic for future research.

Control measures for key contributory factors

In this section, control measures derived from relevant studies are collected and refined. Various measures are obtained at first, however, not all of them are beneficial or effective in controlling corresponding contributory factors. Only measures that have been proved effective and useful by scientific evidence and practical applications in the existing literature are selected, aiming at improving the risk perception and safety awareness of cyclists.

These control measures are illustrated in Table 8 with detailed information.

From Table 8, it is obvious that most control measures are regulated to alleviate the impact brought by the environmental issues and irrational cyclist behaviors. On the contrary, the measures used to control infrastructure issues and judgment errors are either single, or less discussed, which highlights a research gap to fulfil in the future.

In addition, the diversity of control measures in these areas on one hand indicates the complexity and difficulty in controlling them, on the other hand presents the efforts that transport authorities made in creating a safer and friendly cycling environment for more people to cycle on the road.

Future research should conduct an in-depth study on the thoughts and opinions of cyclists on these control measures to see their applicability and feasibility. In light of this research gap, cost benefit analysis could be introduced to justify the selection and implementation of any control measure in an investigated city region.

Conclusion

In this research, a comprehensive review of the state of the art on the key contributory factors influencing cycling safety is conducted based on 81 academic papers collected and refined through a systematic screening process. Methodologically, it newly introduces a risk matrix approach to evaluate and priorities the risk levels of all the involved contributory factors in accident reports. The review articles are then collected based on the selected contributory factors of a high risk level. The distribution of these articles in different aspects further provides a better understanding of the current trends in this research field. By doing so, the in-depth analysis and literature survey on the contributory factors can be more targeted and hence risk control and management for the cycling risk in a concerned area/city can be better addressed.

It is concluded that, whist the contributory factors related to environment, infrastructure, behaviors of road users are well known, less is known regarding the detailed information of these factors. To fulfil the gap, this paper initiates a new in-depth analysis of the characteristics of key contributory factors, relationships among different factors, and control measures for alleviating the impact brought by these factors are carried out subsequently to describe what are the characteristics of these factors, how do they affect the safety of cyclists, what are the relevance between these factors, and what we can do to control their negative effects.

The contribution of this review work is highlighted from the following aspects:

1) Previous studies on cycling safety were most focusing on one specific contributory factor or a limited number of contributory factors, while this paper pioneers the analysis of the key contributory factors influencing cycling safety in a comprehensive way.

2) The data is derived from accident reports and relevant literature and then processed by a risk matrix approach to ensure the integrity of the analysis. It presents a new approach on risk factor identification in which the safety issue of a particular system is analyzed by accident reports, historical failure data to prioritize risk factors. Such factors are further analyzed by a systematic review to understand their characteristics, relationships among the factors of causality, and effective control measures. It will significantly improve cycling safety control effectiveness.

3) It for the first time visualizes relationships among contributory factors and qualitatively describes how such relationships affect cycling safety, with insightful findings disclosed in Section 5.

4) The control measures against different contributory factors are collected, analyzed and selected based on the criterion of their effectiveness in ensuring cycling safety proven by scientific evidence.

5) Key areas for future investigation with urgency are identified.

Future work could analyze the relationships among different contributory factors through advanced quantitative approaches, the effectiveness of control measures proposed to reduce the negative impact of these key contributory factors, the change of these factors with the years and areas, as well as the consideration of those accident cases that are not reported or recorded officially. This is in line with the findings from Winters & Branion-Calles (2017) to an extent.

Data Availability Statement

All data, models, or code used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgements.

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Fig. 1. Risk matrix for contributory factor classification

Fig. 2. Identified key contributory factors

Fig. 3. Article selection flowchart

Fig. 4. Distribution of articles by publication year

Fig. 5. Geographical distribution of related research regions

Fig. 6. Distribution by research methods

Fig. 7. Relationship between key contributory factors