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Factors Contributing to Bicycle-Motorized Vehicle Collisions: A Systematic Literature Review

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Abstract

Bicycle-Motorized Vehicle (BMV) collisions account for the majority of the recorded bicyclists' fatalities and serious injuries. This systematic review intends to examine the main factors contributing to BMV collisions. We performed a comprehensive literature review on Scopus, TRID, ProQuest, and Web of Science databases. Fifty-nine English-language peer-reviewed articles met the eligibility criteria and were included in the final analysis. The main factors contributing to BMV collisions identified were classified in accordance with a recently published conceptual framework for road safety. The majority of studies have identified factors related to road users' behaviour (59.3%) and infrastructure characteristics (57.6%). A minority of studies identified variables related to exposure (40.7%) and vehicles (15.3%) as contributor factors to BMV collisions. A small but significant proportion of studies (20.3%) provided evidence that environmental factors may also play a role, although to a lesser extent, in determining BMV collisions. In addition to the three factors comprised in the applied conceptual framework for road safety, we identified environmental conditions as a category of factors contributing to BMV collisions.

Keywords: bicycle, motorized vehicle, safety, collision, accident, crashes, review

Factors Contributing to Bicycle-Motorized Vehicle Collisions: A Systematic Literature Review

Bicycling is an active mode of transportation that is associated with population-level health benefits (Götschi, Garrard, & Giles-Corti, 2016; Kelly et al., 2014). Furthermore, bicycle, as an alternative to the automobile, holds the potential to reduce traffic congestion, air and noise pollution, and fossil fuel consumption (de Nazelle et al., 2011; Macmillan et al., 2014; Xia, Zhang, Crabb, & Shah, 2013). However, safety concerns are among the most important barriers for cycling (Chataway, Kaplan, Nielsen, & Prato, 2014; Daley & Rissel, 2011; Daley, Rissel, & Lloyd, 2007; Fishman, Washington, & Haworth, 2012; Gatersleben & Appleton, 2007; Heinen, van Wee, & Maat, 2010; Lawson, Pakrashi, Ghosh, & Szeto, 2013; Rondinella, Fernandez-Heredia, & Monzón, 2012; Schepers, Hagenzieker, Methorst, van Wee, & Wegman, 2014). Although fatalities by time spent travelling vary within similar ranges for cycling and driving, risks for cyclists are generally higher than those for motorists (Mindell, Leslie, & Wardlaw, 2012). Bicyclists are considered vulnerable road users because they have no physical protection in the event of a crash with motorized vehicles such as cars or trucks. In addition, compared to bicycles, typical motorized vehicles have greater mass and speed (Wegman, Zhang, & Dijkstra, 2012). Although falls and collisions with non-motorized users may happen more frequently, collisions involving motor vehicles account for the majority of the recorded bicyclists' accidents in police and hospital records (Chong, Poulos, Olivier, Watson, & Grzebieta, 2010; Nicaj et al., 2009; Rosenkranz & Sheridan; Rowe, Rowe, & Bota, 1995; Sze, Tsui, So, & Wong, 2011).

Safety must be improved to enable a shift from motorized transportation to active transportation. Despite the availability of basic data on crash risks, there is limited evidence on the determinants of traffic collisions (Götschi et al., 2016). To reduce the number of collisions between bicycles and motorized vehicles, we need to understand the contributing factors underlying these events. While there have been several literature reviews about the relationship between cycling infrastructure and cycling safety (e.g., Elvik, Vaa, Erke, & Sorensen, 2009; Mulvaney et al., 2015; Reynolds, Harris, Teschke, Cripton, & Winters, 2009; Thomas & DeRobertis, 2013), to our knowledge, none of the previous work have systematically searched for other factors specifically related to BMV collisions. The purpose of this review is to examine the major studies on factors that contribute to BMV collisions. The present review complements earlier reviews on bicycle use and promotion (Handy, van Wee, & Kroesen, 2014; Heinen et al., 2010) by focusing on one of the most important barrier for cycling, that is, safety concerns.

To investigate the factors contributing to BMV collisions based on data from actual collisions, three primary sources are commonly used (Klassen, El-Basyouny, & Islam, 2014): (1) Police records; (2) hospital admission records; and (3) survey records. Each source has its strengths and weaknesses. Police records provide information on the nature, condition, and parties involved in the collision. However, many events may not be reported to police. Medical data can complement police records; however, they may not provide comprehensive information on collisions and their condition. Surveys can provide a wide variety of data about collisions that are not identified or unavailable from police or medical records, but the results may be subjected to several biases (e.g., recall bias). Surveys can also provide information about cycling levels. Little is known about rates of collision per number of cyclists or per kilometre using police records or hospital admission records.

To structure the findings and categorize the factors, we employed a safe systems approach (Allen et al., 2017; Bambach & Mitchell, 2015). Specifically, we adopted a safe systems approach applied to cycling safety (Schepers et al., 2014). According to this approach, crash risk is modelled by exposure (resulting from travel behaviour) and three ‘safety pillars’: infrastructure, road user(s) and vehicle(s). Exposure to risk during traffic participation can be understood as resulting from the interaction between distribution of traffic, modal split, and volumes. Road users refer to human factors and, therefore, a human factors approach was adopted to analyse to factors. Specifically, road users include the following aspects: motorist’s and cyclist’s speed choice, errors, violations, manoeuvres, conspicuity, and substance use. Road characteristics, type of bicycle path, intersection treatment (e.g., speed reducing measures), and type of road section are elements included in the infrastructure category. Finally, the vehicle category encompasses the characteristics of the vehicle in itself and the possible malfunctions, failures, and inadequacies of related equipment.

Materials and Methods

We conducted a systematic review of the literature on the factors contributing to BMV collisions as per the Preferred Reporting Items for Systematic reviews and Meta-Analyses for Protocols (PRISMA-P) statement (Moher et al., 2015).

Literature Search Methods

Two independent investigators performed a comprehensive literature search using Scopus, TRID, ProQuest, PubMed, Google Scholar, and Web of Science databases. The following terms and keywords were used: bicycl*, cycling, cyclist*, mortal*, crash*, death*, fatal*, injur*, accident*, collid*, and collision*. We sought additional literature through the scanning of the bibliographies of relevant articles. These terms were grouped using the Boolean operators ‘and’/’or’. We conducted the full search with the research terms and keywords on February 2016.

Study Selection Criteria

Only studies investigating the factors contributing to BMV collisions were included in the analysis. A contributing factor was defined in our study as any variable that is thought to play a role in determining BMV collisions. Conference abstracts, dissertations, theses, reports, and articles published in non-peer reviewed journals were not included in the review. We decided to include only peer-reviewed articles that were accepted for publication for several reasons (Egger, Juni, Bartlett, Holenstein, & Sterne, 2003; Sterne, Egger, & Moher, 2008). Firstly, unpublished literature does not represent an accepted standard of scholarship because of the absence of peer-review. Secondly, it is not feasible to perform a systematic search and ensure identification of all the relevant unpublished material. The inclusion of unpublished studies can be itself a source of bias due to the unrepresentativeness of the retrieved sample with regards to all unpublished studies. Thirdly, the methodological quality of grey literature tends to be poorly reported and difficult to assess. Fourth, the methodological quality of studies that are difficult to locate tend to be lower than studies that are easily accessible and published in English. This raises the possibility that extensive literature searches could introduce bias by including research of low methodological quality rather than preventing bias. Fifthly, systematic reviews based on published literature tend to produce results that are similar to those obtained from reviews based on more comprehensive searches.

The following selection criteria were used: (1) English-language peer-reviewed article that was accepted for publication in scholarly journals; (2) the study involved the investigation of at least one contributing factor of BMV collisions; (3) the main focus was on cyclists or the results were disaggregated by road user (e.g., vulnerable road users were disaggregated by subcategories that included cyclists); and (4) the outcome of interest was BMV collisions or the results were disaggregated by crash or collision opponent (e.g., crash or collision opponent disaggregated by subcategories that included crash or collision with motorized vehicles). Where no abstract was available the article was not considered for evaluation.

Data Extraction

Two investigators independently performed the data extraction. When discrepancies were found, a third investigator was involved until an agreement was reached. The investigators reviewed the publications and extracted the following data: author(s); year of publication; title; country, year(s) of data collection; source of data; and contributing factors.

Results and Discussion

Publication Selection

The flow of studies through the review process is shown in Figure 1. The combined database searches identified 21,594 records, which we reduced to 8,524 after removing duplicates. Through a review of title and abstract, we further reduced the number of records to 355. Among the 355 full-text articles assessed for eligibility, we also included 11 additional records identified through manual bibliographic check. After full-text articles were assessed for eligibility, we identified 59 articles eligible for inclusion (Figure 1). The 59 publications included in the review were published between 1976 and 2016. Among all the articles selected, half of the publications (52.5%) were from North America and one quarter (25.4%) from Europe. The remaining articles were from Australia (13.5%), and Asia (6.8%). Only one publication (1.6%) reported data gathered in more than one country, in particular USA and EU.

Publication Findings

Appendix 1 displays the categorization of factors contributing to BMV collisions according to the three main pillars described by Schepers et al. (2014) in their conceptual framework for road safety and mobility. Moreover, we have included the exposure to risk, which in the model is directly related to crash risk. We have also included environmental factors that were not included in the framework. Environmental factors refer to any element external to the road infrastructure that may influence road safety. This include biotic factors such as human activity outside the road or roadside vegetation, as well as abiotic factors such natural forces as the weather. Based on the review of the studies, in this category, we included factors related to daylight conditions, season conditions, tourism, or vision obscurement due to contextual characteristics. Figure 2 displays the number of studies that examined each factor, where the width of the arrow represents the number of studies that investigated variables related to the factor. As can be easily seen, the majority of studies have investigated factors related to the behaviour both of the cyclist and the driver of the opponent vehicle involved in the collision (road user: 35 studies; 59.3%) and to the road and/or infrastructure characteristics (road infrastructure: 34 studies; 57.6%). More than one out of three studies investigated factors related to exposure (including traffic volume and safety in numbers effect: 24 studies; 40.7 %) whereas less than ten articles explored factors related to the vehicle (vehicle: 9 studies; 15.3%). Finally, one out of four articles investigated the environmental factors (environmental: 12 studies; 20.3%). The details of the factors contributing to BMV collisions are reported in Appendix 2 and 3. Table 1 lists each of the factors and tally how many studies show protective or risk effects. As can be easily seen, most of the studies focussed on risk effects.

Road User

The road user(s) category refers to behavioural factors of the cyclist and/or the driver of the opponent vehicle. We differentiated and classified them into violations, errors, critical manoeuvres, use of visibility aids, substance use, and training. Violations and errors are the most studied contributing factors related to road user(s).

Violations: Behaviours that resulted in infringement of road rules were grouped as violations. Not respecting the traffic signals (e.g., signs, signals, markings) or failing to properly yield at an intersection by both cyclist (Ashbaugh, Macknin, & VanderBrug Medendorp, 1995; Atkinson & Hurst, 1983; Hamann, Peek-Asa, Lynch, Ramirez, & Hanley, 2015; Hunter, Pein, & Stutts, 1995; K. Kim & Li, 1996; Liu, Shen, & Huang, 1995; Nicaj et al., 2009; Vandenbulcke et al., 2009; Wessels, 1996; Williams, 1976; Yan, Ma, Huang, Abdel-Aty, & Wu, 2011) and driver of the opponent vehicle (Ashbaugh et al., 1995; Atkinson & Hurst, 1983; Eilert-Petersson & Schelp, 1997; Garder, 1994; Hamann et al., 2015; Hunter et al., 1995; K. Kim & Li, 1996; Nicaj et al., 2009; Sayed, Zaki, & Autey, 2013; Vandenbulcke et al., 2009; Vandenbulcke, Thomas, & Int Panis, 2014; Wang & Nihan, 2004; Wessels, 1996; Yan et al., 2011) were the most investigated types of violation. Other cyclists' violations commonly associated with collisions were riding against traffic, in a wrong-way, or coming from an unexpected side of the road (Ashbaugh et al., 1995; Atkinson & Hurst, 1983; Hamann et al., 2015; K. Kim & Li, 1996; Räsänen, Summala, & Pasanen, 1998; Vandenbulcke et al., 2014; Wachtel & Lewiston, 1996; Wessels, 1996). Besides, one study has found an association between increased risk of collisions and the automobile operating speed (Liu et al., 1995).

Errors: Behaviours that resulted in an unintentional deviation or failure to achieve a desired outcome were grouped as errors. Several studies showed an association between collisions and cyclist's left or right turn, ride outs or sudden swerves without scanning behind for incoming traffic (Ashbaugh et al., 1995; Atkinson & Hurst, 1983; Hamann et al., 2015; Hoque, 1990; Hunter et al., 1995; Liu et al., 1995; Rowe et al., 1995). Concerning motorized vehicles, failure to pull out correctly from a parking space or a driveway (Ashbaugh et al., 1995) as well as failure to see a cyclist (Atkinson & Hurst, 1983; Hoque, 1990; McCarthy & Gilbert, 1996; Rowe et al., 1995) were related to collision. Road users' (both cyclists and motorists) inattention, misjudgement, or inexperience were frequently indicated as a source of errors (Atkinson & Hurst, 1983; Garder, 1994; Gaudet et al., 2015; K. Kim & Li, 1996; Liu et al., 1995; Nicaj et al., 2009; Stimpson, Wilson, & Muelleman, 2013). We could also hypothesize that inexperience or inattention may lead to another type of error often studied in the literature, such as the loss of control of the vehicle and the non-compliant occupation of road lane or bikeway. These types of errors have been found to increase the likelihood of having a collision (Ashbaugh et al., 1995; Rowe et al., 1995; Vandenbulcke et al., 2009; Wessels, 1996; Yan et al., 2011).

Critical manoeuvres: Several studies provided details about the type of manoeuvres that can be considered critical. Most of the studies focussed on right- or left-turning motor vehicle (Gerberich, Parker, & Dudzik, 1994; Miranda-Moreno, Strauss, & Morency, 2011; Räsänen & Summala, 1998; Räsänen et al., 1998; Summala, Pasanen, Räsänen, & Sievänen, 1996; Wang & Nihan, 2004; Williams, 1976). Two studies provided evidence that a specific type of turning manoeuvre was associated with collision: a motorist turning across a cyclist path (Atkinson & Hurst, 1983; Hunter et al., 1995). When a motorist is turning at an intersection, the scanning strategy could be focussed on traffic situation coming from the lawful direction, overlooking the wrong-way traffic. These results are consistent with "looked-but-failed-to-see" crashes due to driver's inadequate scanning strategy, visual search strategies, and misplaced expectations (Räsänen & Summala, 1998; Räsänen et al., 1998; Summala et al., 1996). Other common critical motorized vehicle manoeuvres were overtaking (Atkinson & Hurst, 1983; Gerberich et al., 1994; Hoque, 1990; Hunter et al., 1995; McCarthy & Gilbert, 1996), and door opening (Johnson, Newstead, Oxley, & Charlton, 2013; Teschke et al., 2014; Vandenbulcke et al., 2009). Two studies reported two critical manoeuvres concerning bicycle-truck collision: cyclists attempting to pass trucks on the nearside (i.e., the side of a vehicle normally closer the kerb) at junctions (Frings, Rose, & Ridley, 2012) and trucks overtaking or being alongside the cyclists (McCarthy & Gilbert, 1996). Blind spots, above all in large vehicles, could be an explanation for the increased risk when overtaking (Pai, 2011).

Use of visibility aids, substance use, and training: Several studies investigated if use of visibility aids may influence the risk of collision. In this section, we consider the usage of visibility aids by the cyclists and the consequences of their chosen strategy to be more visible to the other road users. Few studies have found an increased risk of collisions among cyclists that did not have one or more visibility aids (Hagel et al., 2014) and had low level of usage visibility aids in low light conditions (Lacherez, Wood, Marszalek, & King, 2013; Twisk & Reurings, 2013). However, the protective effect of visibility aids varied based on light conditions and, in some cases, the use of visibility aids may not prevent the risk of collisions (Hagel et al., 2014; Tin Tin, Woodward, & Ameratunga, 2014). One likely explanation is that the use of visibility aids is also associated with exposure because frequent cyclists are more likely to wear highly visible clothing (Teschke et al., 2012). Furthermore, under poor visibility condition, the car driver may fail to detect the cyclist and react in time; research has also found how cyclists overestimate at what distance they would be visible (Wood, Lachereza, Marszaleka, & King, 2009). Although visibility aids have the potential to improve detection and recognition, the effect of visibility aids on BMV collisions remains unknown (Kwan & Mapstone, 2004, 2006). Alcohol use by both cyclists and motorists (Nicaj et al., 2009; Rowe et al., 1995; Twisk & Reurings, 2013) was associated with higher risk of BMV collision. Finally, receiving a dedicated cycling training, aimed to improve road safety awareness and knowledge, did not affect the likelihood to get involved in a collision (Frings et al., 2012).

Exposure

An increased risk of collisions was related to exposure to risk resulting from travel behaviour (Martínez-Ruiz et al., 2014; Wei & Lovegrove, 2013; Wessels, 1996). This relationship has been tested using different indicators of exposure, such as bicycle commuting (Hagel et al., 2014), number of days of cycling (Fuller, Gauvin, Morency, Kestens, & Drouin, 2013; Hagel et al., 2014), total number of trips (P. Chen, 2015), time spent cycling (Tin Tin, Woodward, Thornley, & Ameratunga, 2011), and total lane kilometres and bicycle lane kilometres (Wei & Lovegrove, 2013). Few studies found an increased risk of collisions associated with cycling during weekday peak time (Hagel et al., 2014; Kloeden, Hutchinson, & Long, 2007). The role of exposure could be explained by the fact that the road is a context with intrinsic risks and exposure corresponds to an increased probability that one of these risks translates into a collision.

Vehicle miles of travel were not associated with an increased risk of collisions (Dumbaugh & Li, 2010) and, therefore, do not seem to be a valid measure of risk exposure for bicycle crashes. Several studies revealed that the number of cyclists as well as the traffic volume could play a role in BMV collision. It seems intuitively obvious that several studies have shown that the risk of collisions is associated with motorized vehicle traffic volume (M. Kim, Kim, Oh, & Jun, 2012; Lee, Abdel-Aty, & Jiang, 2015; Liu et al., 1995; Nordback, Marshall, & Janson, 2014; Romanow et al., 2012; Schepers, Kroeze, Sweers, & Wüst, 2011; Wei & Lovegrove, 2013).

Although the number of collisions increases with increments in bicycling exposure, the probability that a motorist might collide with a cyclist would decline with an increase in the number of people cycling (Jacobsen, 2003; Kaplan & Giacomo Prato, 2015; Minikel, 2012;

Nordback et al., 2014; Räsänen et al., 1998; Tin Tin, Woodward, & Ameratunga, 2013; Tin Tin et al., 2011; Vandenbulcke et al., 2014; Wang & Nihan, 2004; Wei & Lovegrove, 2013). This effect is called safety in numbers. According to Jacobsen (2003), the safety in numbers effect, rather than being due to changes in traffic laws, social mores or roadway design, is probably due to awareness of cyclists among drivers and their behavioural adaptation in the presence of cyclists. Moreover, the more people cycle, the fewer will take other means of transportation (possibly motorized-vehicles), thereby reducing the probability of collision.

Vehicle

Vehicle characteristics play a role in BMV collisions. We found studies that investigated the characteristic of the vehicle itself, as well as other studies focussed on the malfunction, failure, and inadequacy of equipment.

Concerning the former, a couple of studies revealed that increasing levels of van, large automobile, and truck traffic were associated with higher collision risks (Ackery, McLellan, & Redelmeier, 2012; Vandenbulcke et al., 2014). Compared to cars, buses and heavy vehicles have more blind spots and cyclists in the blind spot of a huge goods vehicle entailed higher a risk of collisions (McCarthy & Gilbert, 1996), especially when buses and heavy vehicles turned right at intersections (Kaplan & Giacomo Prato, 2013; Vandenbulcke et al., 2014). Larger size of the vehicle contributes to increase the risk of BMV collisions because of a more cumbersome manoeuvrability as well as and increased presence of blind spots. Furthermore, several studies provided evidence that risk of collisions was associated with inadequacy of lights on bicycles (Hoque, 1990), and malfunctions of the bicycle (Ashbaugh et al., 1995) such as brake related defects (Nicaj et al., 2009).

Infrastructure

Many studies focussed on infrastructure characteristics. Several studies found an increased risk of collisions at intersection compared to other road section (L. Chen et al., 2012; Kaplan & Giacomo Prato, 2015; Romanow et al., 2012; Stone & Broughton, 2003; Wei & Lovegrove, 2013; Wessels, 1996). Concerning the type of intersection, one study revealed that the four leg intersections increased the risk of collisions (Dumbaugh & Li, 2010), whereas another study reported that the number of intersection legs did not influence the risk of collisions (Miranda-Moreno et al., 2011). Moreover, there is evidence that roundabouts may increase the risk of BMV collisions (Kaplan & Giacomo Prato, 2015; Vandenbulcke et al., 2014). The evidence from the present review supports the idea that the conversion of intersections to roundabouts may increase the likelihood of BMV collisions (Mulvaney et al., 2015).

Other studies focussed on the bicycle infrastructure. The absence of bicycling infrastructure was cited in many of the publications as a contributing factor to BMV collision, which aligns with the fact that exposure to traffic increases risk of collisions (P. Chen, 2015; Hagel et al., 2014). Vandenbulcke et al. (2014) found that cycling on marked cycle lanes built in roundabouts (see supplemental material) leads to a higher crash risk for cyclists compared to roundabouts without any cycle facility. Bridges without cycle facilities increased the risk of collisions (Vandenbulcke et al., 2014), whereas wider passenger roads (sidewalk) decreased the risk of collision (M. Kim et al., 2012). Although two studies have found that bike lanes (see supplemental material) are associated with a lower risk of collision (P. Chen, 2015; Lott & Lott, 1976), another study reported that bike lanes did not influence collisions (L. Chen et al., 2012). In addition, other studies have reported increased risk of collision in bicycle lanes (P. Chen, 2015; Wei & Lovegrove, 2013). Possible explanations for these contradictory findings are increased numbers of cyclists and increased speed among cyclists (Elvik et al., 2009) or the fact that bicycle lanes are not physically separated from motorized traffic. Copenhagen-style bicycle paths (i.e., road–curb–bicycle path–curb–sidewalk, see supplemental material), where separation from motorized vehicles is guaranteed to the cyclists, are less likely to lead to collisions (Kaplan & Giacomo Prato, 2015). Thus, the absence of a barrier between bicycling infrastructures and that of other road users or a small separation or space between them might facilitate interaction with motorized vehicles, thereby, leading to higher risk of collision. Indeed, roundabouts with cycle lanes marked as part of the circulating carriageway might increase BMV collisions whereas roundabouts with cycle paths might reduce the likelihood of BMV collisions (Mulvaney et al., 2015; Reynolds et al., 2009). A distance of 2–5m between the cycle track (see supplemental material) and the side of the main carriageway decreased the risk of collision (Schepers et al., 2011). Concerning the importance of separation, another study found that the quantity of unclear borders (e.g., defined separation of space by a physical barrier) was associated with increased risk of BMV collisions (D. Kim & Kim, 2015). A defined separation of space by a physical barrier can reduce the invasion of sidewalks by motorized vehicles. The use of separated bicycle paths was cited as one of the factors that reduces the odds of BMV collisions on busy streets (Thomas & DeRobertis, 2013) as well as contribute to the high level of cycling safety in the Netherlands (Schepers, Twisk, Fishman, Fyhri, & Jensen, 2016). However, there is evidence that separated cycle paths, whilst being safer in general, might increase the risk of collisions at intersection. In addition, discontinuity points (i.e., intersections and roundabouts) in urban areas with a widespread bicycle infrastructure increased the risk of collisions (Kaplan & Giacomo Prato, 2013). Another study found an increased risk of collisions in cases of close vicinity (≤ 0.9 m) between separated cycle lanes (see supplemental material) and parking facilities (Vandenbulcke et al., 2014). The fact that separated cycle paths increase the risk of collisions at intersection might be due to the fact that, once cyclists are segregated from traffic, drivers and cyclists are not used to encounter each other, thus reducing their awareness and not expecting to find them neither at intersections (Elvik et al., 2009). In addition, there is evidence that two-way bicycle paths have a higher risk of BMV crashes at unsignalized intersections compared to one-way bicycle paths. Finally, bicycle path could increase the risk of BMV collisions at intersection (Wachtel & Lewiston, 1996), especially if the bicycle path is a two-way cycle track (Räsänen & Summala, 1998; Räsänen et al., 1998; Schepers et al., 2011). The most likely reason is that, in the case of right-hand driving, drivers turning right do not focus their attention on cyclist coming from the right (Summala et al., 1996). On the contrary, the implementation of one-way bicycle paths was found to contribute to the safety of urban cycle tracks (Thomas & DeRobertis, 2013) as well as to the high level of cycling safety in the Netherlands (Schepers et al., 2016).

To address the issues associated with separation at crossroad, several studies focussed on the safety effect of road markings at bicycle crossings. A triangular warning sign painted on the pavement with bicycle crossing painted red (Räsänen et al., 1998) as well as the presence of raised bicycle crossing or other speed reducing measure for vehicles entering or leaving the side road (Schepers et al., 2011) have been found to decrease the risk of collision. However, red colour and high quality marking for bicycle crossing may increase the risk of collision (e.g., due to risk compensation). Possible reasons are they increase cyclists' speed and diminish their visual scanning (Schepers et al., 2011).

Several studies revealed that urban or metropolitan roads or arterial roads were more dangerous (Dumbaugh & Li, 2010; Kaplan & Giacomo Prato, 2015; Liu et al., 1995; Minikel, 2012; Wessels, 1996). In addition, the presence of retail or service establishments (Romanow et al., 2012) or strip commercial uses (Dumbaugh & Li, 2010) increased the risk of collision. Traffic volume may explain these findings. Indeed, it has been shown that roads with insufficient capacities cannot adequately accommodate both bicycles and motor vehicles during rush hours, thus, increasing the risk of collisions (Liu et al., 1995). Not only the volume of traffic seemed to increase the risk of collisions but also the speed, the density or the presence of road and traffic signal (P. Chen, 2015; Wei & Lovegrove, 2013) as well as the number of bus stops or in close proximity to them (Chaney & Kim, 2014; D. Kim & Kim, 2015; Miranda-Moreno et al., 2011; Wei & Lovegrove, 2013). The change in traffic flow around bus stops as well as the vision obscurement due to the presence of a large vehicle (Eilert-Petersson & Schelp, 1997) could explain may explain the increase in collision.

The presence of structured medians (see supplemental material) — both barrier and planter medians — (D. Kim & Kim, 2015) or divided road (Yan et al., 2011) seemed to decrease the risk of collisions because medians were significant obstacles for cyclists, discouraging them from illegal crossing. In addition, some structured medians also serve as a refuge for cyclists when crossing streets, allowing them to cross in two steps. However, a study has found that presence of a median did not influence the risk of collisions (Miranda-Moreno et al., 2011).

Other studies focussed on the restricted or partly restricted visibility associated with road characteristics. The risk of collisions was higher in case of inadequacy of street lighting (Hoque, 1990), limited sight angle for the drivers (Sayed et al., 2013), high buses or shrubbery obscuring the vision (Eilert-Petersson & Schelp, 1997), path obstructions (Romanow et al., 2012), intersections with restricted or partly restricted visibility (Räsänen et al., 1998), blind conflicts at intersections (Wachtel & Lewiston, 1996), and arterials and subarterial roads with more entrances and exits with insufficient sight distance (Liu et al., 1995).

Apart from visibility, the presence of entrances and exits seemed to play a role in collisions probably because the discontinuation of sidewalks presents a serious hazard to bicyclists (D. Kim & Kim, 2015). An increased risk of collisions was associated with parking lot entranceways (D. Kim & Kim, 2015), presence of garage/parking driveway (Vandenbulcke et al., 2014), bridge and tunnel portals (i.e., entrances and exits) (Slaughter et al., 2014). However, in the study of Miranda-Moreno et al. (2011) the presence of parking entrance was not associated with an increased risk of collision. Finally, some studies revealed that road surface hazards such as sand, gravel, steepness, road curve, uneven or wet surface increased the risk of collisions (Gerberich et al., 1994; Nicaj et al., 2009; Yan et al., 2011).

Infrastructure characteristics aimed at reducing speed have been related to a decrease in BMV collisions (Räsänen et al., 1998; Summala et al., 1996; Wang & Nihan, 2004). In addition, higher driving speed limits were associated with more bicycle crashes collisions (P. Chen, 2015; Stone & Broughton, 2003) while a decrease in collisions was found in zones with low speed (Lee et al., 2015). Some studies reported specific posted speed limits to be associated with higher likelihood of collision: speed limit >30 km/h (Hagel et al., 2014), posted speed >56km/h (Ackery et al., 2012), and high speed limit zones, i.e., 75 km/h (Hoque, 1990).

Environment

In the last category, we included all the factors related to the social and environmental context. One study had shown how living in a higher density population area, especially if that population was prone to use private mode of transport, increased the bicycle collision rate by overcrowding the shared motorway (Chaney & Kim, 2014). Another study demonstrated that collisions are more likely in zones with many tourist attractions (Lee et al., 2015). It may imply that tourists who are not familiar with local roadways and rules are more prone to traffic crashes, nonetheless, it could also be due to an increase of traffic exposure nearby touristic places.

Two studies mentioned vision obscurement (Garder, 1994; Hamann et al., 2015) as a factor contributing to collision; however, more information about vision obscurement was not provided. We note that there are different types of obscurement and they can increase the likelihood of collisions in several ways. In the other category, we also included the role of lighting conditions on the likelihood of BMV collision. Reduced lighting (dusk, dawn, unlighted roadway) or darkness seemed to increase the odds of a collisions (Hagel et al., 2014; Hamann et al., 2015; Liu et al., 1995), and its relative risk of having a fatal collision, that was several times higher than when bicycling during daylight (Noordzij, 1976). Although it seems intuitively obvious that the risk of collisions increases as lighting conditions worsen or at night, other third variables can lead to a mistaken causal relationship between light condition and collision. For instance, at night, a road can be less congested which, in turn, let the driver operate at faster speed (Liu et al., 1995), thereby increasing the likelihood of a BMV collision. Moreover, another study, by contrast, has demonstrated that street light conditions did not have a significant impact on the likelihood of BMV collisions (D. Kim & Kim, 2015).

Other studies focussed on adverse weather conditions. During winter and autumn seasons, weather conditions have been linked to a higher rate of cyclist-motorist crashes due to adverse road surface conditions (Kaplan & Giacomo Prato, 2013). This could be due to the low visibility of such seasons and the road surface conditions (Kaplan & Giacomo Prato, 2013). However, such findings might not apply to other countries with milder and not so changing weather conditions. Another study found that in July, there was a higher probability for the cyclist to have a crash with a motorized-vehicle. This could be due to the hot weather on cognitive performance (Liu et al., 1995) or also to an effect of exposure, that is, due to nicer weather, more people might go out with the bicycle and therefore, opportunities for crashes might increase (Chaney & Kim, 2014). Finally, one study focussed on evaluating the effectiveness of a public bike sharing program, without proving a reduction (even an increase) in the likelihood of collisions and near misses (Fuller et al., 2013).

Practical Implications

This review suggests some implications for practitioners. First, given that several studies found intersections to be linked to BMV collisions, we consider it a key factor to be addressed when planning and designing road infrastructures, perhaps, by means of speed-reducing initiatives that have shown to work (Wang & Nihan, 2004). Specifically, speed-reducing measures, such as speed limit for the opposing approach (Wang & Nihan, 2004), speed bumps, elevated bicycle crossings, and stop signs, could help motorists begin visual searching behaviours at non-signalized intersections earlier and detect bicycles properly (Summala et al., 1996). It is obvious that slower speeds can give cyclists and motorists more time to detect the opposing vehicle and conduct stop or evasive actions when necessary. For instance, the implementation of speed-reducing measures (e.g., speed humps) at unsignalized intersections in the Netherlands has prevented 2.5% of cyclist fatalities (Schepers et al., 2016). In addition, posted speed limits seem to play a role in BMV collisions. The results of posted speed limits in our study are in line with those of a recent study that found a reduction of cyclist casualties by means of 20 mph speed restrictions in urban areas (Mulvaney et al., 2015).

Second, to reduce the risk of collision, the distribution of traffic over the road network is important. According to Schepers et al. (2016), a ‘network level separation’ might reduce cyclists’ exposure to motorised traffic by shifting away motor vehicles from streets with high cycling levels. Specifically, cyclists' exposure to high-speed traffic is reduced through the implementation of large traffic-calmed areas, a rough distributor road network for motorised traffic, and a heavily used freeway network.

Third, devices that help cyclists detect vehicles and vice versa could be useful, especially at intersection, during overtaking manoeuvres, and to avoid door opening collisions. Door opening collisions may also be prevented by providing enough width between parked cars and cycling infrastructures (Lusk, Morency, Miranda-Moreno, Willett, & Dennerlein, 2013). Shifting bicycle infrastructures away from parking bays might be needed in order to reduce this type of collisions (Johnson et al., 2013)

Fourth, the effect of season on BMV collisions suggests that some measures could be adopted. For instance, during winter or autumn especially in Northern Europe in case of limited daylight hours and inclement weather, road surface needs to be taken special care, possible hazards need to be prevented or removed, and visibility aids need to be applied on road objects.

Finally, educational campaigns as well as educational programs for both bicyclists and drivers could benefit cyclist's safety. However, to our knowledge, there is a lack of evidence of the effectiveness of educational campaigns and educational programs in reducing BMV collisions. For instance, a previous systematic review revealed that educational and skills training bicycling programmes are associated with an increased knowledge of cycling safety, but this does not seem to translate into cycling safety (Richmond, Zhang, Stover, Howard, & Macarthur, 2014).

Further Research Needs

Individual factors such as cycling and driving experience or cyclist's and driver's attitudes or skills may be additional contributing factors, but this would need to be substantiated in future research. An aspect overlooked in the literature on BMV collisions is drivers' and cyclist's speed. A lower speed could help cyclists and drivers detect other vehicles and offers greater reaction times to avoid collisions. Low cycling speed was listed among the most important risk factors contributing to the high level of cycling safety in the Netherlands (Schepers et al., 2016). Moreover, we were not able to find evidence concerning the influence of latent individual characteristics such as driving style, mood, distracted driving, motivations to cycle and cyclists' experiences and victimization (English & Salmon, 2016; Heesch, Garrard, & Sahlqvist, 2011; Kaplan & Prato, 2016; O'Connor & Brown, 2010; Paschalidis, Basbas, Politis, & Prodromou, 2016) on BMV collisions.

The presence of intersection was cited in many of the publications as a contributing factor to BMV collision. However, P. Chen (2015) stated that a higher number of intersections might also reduce the speed of road users which, in turn, let road users have more time to scan the environment and increase the probability to detect cyclists, thereby reducing the risk of BMV collision. There is need for examining other factors present in the intersection that could be explaining these differences in findings. Furthermore, not all types of intersection might have the same influence on BMV collisions. In our opinion, discrepancies in findings across studies are likely to reflect the lack of well-designed evaluation studies of cycling infrastructure. A recent systematic review on the influence of cycling infrastructure on cycling injuries highlights the lack of high quality evidence to be able to draw firm conclusions in terms of the effect of cycling infrastructure on cycling collisions (Mulvaney et al., 2015). Most of the studies that investigated the relationship between different types of infrastructure and collisions did not collect information on the numbers of cyclists that are actually using it (Elvik et al., 2009). Thus, little is known about rates of collision per number of cyclists using different types of infrastructure.

Since bicycle and road saliency have been identified as an important factor for collisions risk for cyclists (Thompson, Savino, & Stevenson, 2016), there is need to study how signs can raise awareness about the presence of cyclists and might affect cycling safety in such type of infrastructures. Furthermore, the available evidence does not allow us to provide recommendations regarding the use of wide curb lanes or bike lanes, and their suitable widths (Taylor & Davis, 1999). Future research could also examine the influence of network level separation on the likelihood of BMV collisions through its effect on reduced exposure to high-speed motor vehicles.

Despite the importance of exposure for bicycle safety research, the majority of the studies included in our review did not collect exposure. This finding is in line with that of a recent review on exposure measurement in bicycle safety analysis (Vanparijs, Int Panis, Meeusen, & de Geus, 2015). Future studies should collect information on exposure and control for it during the analyses.

The influence of a variable may differ according to specific condition or situation. For instance, a specific risk or protective factor may be important when considering one typology of collision but, at the same time, it may be negligible for different conditions. The results of the present review suggest that bicycle crashes occur under different conditions and type of crash. Thus, it is necessary to take into account the systematic heterogeneity in bicycle crashes. To account for the heterogeneous nature of the crash data, future studies can use a latent class clustering approach. By identifying homogenous bicycle crash groups, researchers and practitioners can identify the most important risk and protective factor and the appropriate safety countermeasures for different bicycle crash types occurred under different conditions.

Since the reviewed studies focussed on the physical environment, future research should investigate the role played by social and cultural environment. For instance, there is evidence of differences in safe cycling culture among countries (Nabipour, Nakhaee, Khanjani, Zirak Moradlou, & Sullman, 2015). As another example, observational studies revealed the influence of social pressure and herding behaviour in violations among cyclists (Fraboni, Marin Puchades, De Angelis, Prati, & Pietrantoni, 2016; Johnson, Newstead, Charlton, & Oxley, 2011; Wu, Yao, & Zhang, 2012). In addition, basic research and in-depth studies focusing on the adherence to national design criteria of existing infrastructures (Taylor & Davis, 1999), as well as on parameters and circumstances of the collisions (e.g., driving speed, distance between bicycle and motorized vehicle, impact location, reaction time, and trajectories) can shed light on new and unexpected factors contributing to BMV collisions. Finally, most of the studies included from our search reported the most frequent or typical characteristics of BMV collisions; however, without reliable exposure data (Vanparijs et al., 2015), meaningful analysis and interpretation of potential factors contributing to BMV collisions are hindered.

Limitations

This study has several limitations which should be recognized. First, associations identified in cross-sectional studies, which are carried out at a single point in time, should not be considered as a causal relationship. Second, retrospective studies may be prone to recall bias. Third, we did not include the 'grey literature' as it did not fulfil the quality criteria of being peer reviewed and accepted for publication in scholarly journals. Although the grey literature might include well-designed studies, its quality is often uncertain and varies considerably. Moreover, it is notoriously difficult to discover, access, and evaluate. Fourth, some of the intervention studies did not collect information about exposure. Finally, we acknowledge the fact that road accidents risk varies according to different variables such as gender, age, social class, ethnicity or countries (Elvik et al., 2009; Talbot, Reed, Barnes, Thomas, & Christie, 2014). These variables were not included in our study because we focussed on factors directly related to BMV vehicle collision. For instance, there is no theoretical reason to suppose that male gender is a cause of BMV vehicle collision. Male cyclists may be more likely to have a BMV vehicle collision compared to female cyclists but the reasons are others (different exposure, violations, speed, etc.).

Conclusions

The aim of this systematic review was to investigate the factors contributing to BMV collisions. To this end, we examined 59 peer-reviewed publications that met our eligibility criteria. These publications reported findings collected over a period of 40 years. We have found an overemphasis on road user factors and infrastructure at the expense of other factors. A minority of studies identified variables related to vehicle(s) and exposure as contributing factors to BMV collisions. Some studies provided evidence that environmental factors may also play a role in determining BMV collisions. It is precisely for this reason that we propose to include environmental factors as a relevant category of contributing factors to BMV collisions.

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Table 1
Factors Contributing to BMV Collisions and Body of the Evidence

Factor	Risk effect	Protective effect	Neutral
High speed limits	4		
Vehicle and bicycle speed	1		
Large vehicles	2		
Cyclists generic errors (e.g., suddenly swerving, midblock ride out)	15		
Cyclists generic violation	4		
Exposure	8		
Bicycle lane	2	2	
Presence of intersections of different types	8	2	1
Arterial road	3		
Bicycle volume		5	
Riding in a bunch	1		
Driver failing to yield	10		
Bicyclists failing to yield	7		
HGV blind spot when turning	2		
Riding the wrong way	7	1	
Traffic volume	5	1	
Turning right	4	1	
Two-way cycle tracks	2		
Driver errors	15		
Driver violations	1		
Insufficient light	9		1
Presence of bus stops	4		
Cyclist conspicuity aids	1	1	
Absence or inadequacy of visibility aids	4		1
Driver's potentially dangerous manoeuvres	9		
Adverse road surface conditions	5		
Safety in Numbers		4	
Peak hours	2		
Mechanical failures	2		
Drivers' fatigue	1		
Both bicyclists' and drivers' human factors (e.g., inattention)	10		
Presence of median		1	1
Width of passenger road (i.e., sidewalk)		1	
Absence of physical barriers	2		
Discontinuity points in infrastructure	3		
Alcohol and substance use	3		

Vision obstruction	4		
Density of road signals	3		
Parking entrances and vicinity to parking facilities	3		1
Cyclist inexperience	1		
Misplaced expectations about the other’s behaviour	3		
Speed reduction measures	1	4	
City streets	2		
Residential areas		1	
Bikeability training			1
Pavement signs	2	1	
Number of right-turn lanes	2		
Intersections with cycling lanes	2		
Limited visibility for drivers	2		
Public bike sharing program			1
Utilitarian cycling	1		
Commercial area	2		
Two-way cycle tracks at intersections	1		
Safe cycling practices (e.g., not riding on the road, being aware of buses at intersections)		2	
Riding a road bike	1		
Having a crash history	1		
Touristic zone	2		
Insufficient road capacity	1		
Complete separation from traffic		1	
Population density	1		
Ratio of time spent cycling to time spend using the car		1	
Neighbourhood ethnicity	1		
Land use mixture	1		
Density of off-arterial bike lanes		1	
Vehicle miles travelled			1
speed limit over 30 km/h	1		
Path obstructions	1		
2–5m distance between cycle-track and the main carriageway	1		
Bridge and tunnel portals (i.e., entrances and exits)	1		
Major streets with parked cars and no infrastructure bike	1		
Vehicle door opening	1		
Low level of cycling	1		
Riding on marked cycle lanes built in roundabouts (outer lane)	1		
Complexity of a location	1		
Bridges without cycle facilities	1		
Intersections equipped with traffic lights and marked cycle lanes	1		

Presence of on-road tram tracks and (tracks) crossings	1		
Bicycling on the roadway in the same direction as adjacent traffic			1
Blind conflicts at intersections	1		
sidewalk or bicycle path in comparison to roadway	1		
Pedestrian overbridges	1	1	
Visual noise level	1		
Width of the entering approach		1	
Number of outgoing lanes	1		
Road median width	1		
Number of intersection approaches sheltered by elevated roadways	1		
Signal control pattern with four-phases		1	
Speed limit (km/h) for the opposing approach		1	
Total lane kilometres	1		
Number and percentage of driver commuters		1	
Operating without the required equipment	1		
Divided road		1	

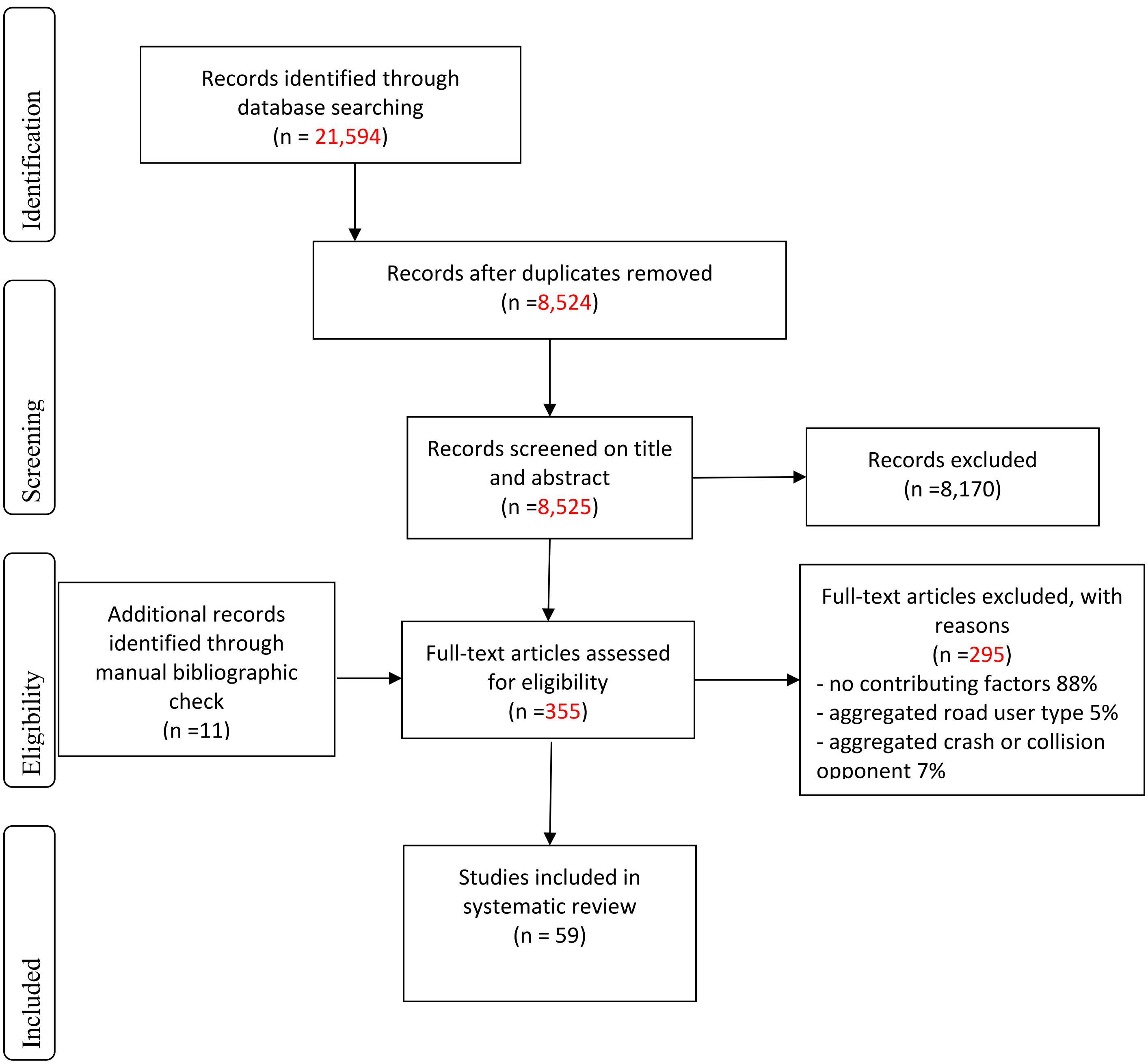

Figure 1. Publication identification, screening, eligibility and inclusion

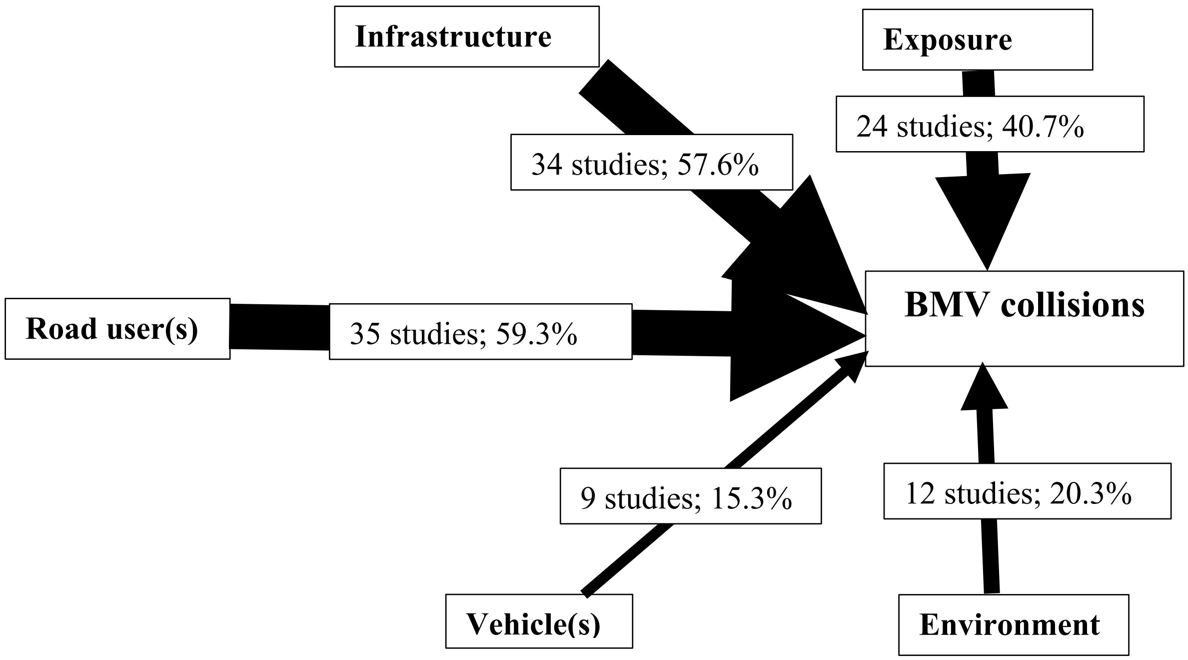

Figure 2. Number of studies that investigated each factor

Note. The width of the arrow represents the number of studies that investigates the factor.