Impact of transportation infrastructure on bicycling safety (Review)

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Abstract

Background: Bicycling has the potential to improve fitness, diminish obesity, and reduce noise, air pollution, and greenhouse gases associated with travel. However, bicyclists incur a higher risk of injuries requiring hospitalization than motor vehicle occupants. Therefore, understanding ways of making bicycling safer and increasing rates of bicycling are important to improving population health. There is a growing body of research examining transportation infrastructure and the risk of injury to bicyclists.

Methods: We reviewed studies of the impact of transportation infrastructure on bicyclist safety. The results were tabulated within two categories of infrastructure, namely intersections or "straightaways" (roads, lanes, paths). To assess safety, studies examining the following outcomes were included: injuries; injury severity; and crashes (collisions and/or falls).

Results: The literature to date on transportation infrastructure and cyclist safety is limited by the incomplete range of facilities studied and difficulties in controlling for exposure to risk. However, evidence from the 23 papers reviewed (8 that examined intersections and 15 that examined straightaways) suggests that infrastructure influences injury and crash risk. Intersection studies focused mainly on roundabouts. They found that multi-lane roundabouts can significantly increase risk to bicyclists unless a separated bike path is included in the design. Studies of straightaways grouped facilities into few categories, such that facilities with potentially different risks may have been classified within a single category. Results to date suggest that sidewalk cycling has the highest risk, major roads are more hazardous than minor roads, and the presence of bicycle facilities (e.g., marked bicycle lanes and paths) was associated with the lowest risk.

Conclusions: Improvements to bicycling-related infrastructure in North America could reduce injury rates, and evidence is beginning to accumulate for guidelines to be adopted for cyclist safety. The major advantage of infrastructure-based improvements, compared to personal protective devices such as helmets, is that safe infrastructure provides population-wide, continuous and passive protection that prevents injury events. Future

research should examine a greater variety of infrastructure and control for exposure to risk and for confounding factors.

Background

Bicycling is an active mode of transportation that integrates physical activity into daily life. The bicycle is an attractive alternative to the automobile as an urban mode of transport. Cycling is associated with a range of individual and public health benefits such as improved fitness and decreased obesity and cardiovascular disease risk [1-4], as well as ancillary benefits such as reduced emissions of noise, air pollutants and greenhouse gases [5]. There are significant economic costs of physical inactivity [6], and benefit-cost analysis suggest that the benefits of increased cycling are worth approximately 4 to 5 times the costs of investing in new cycling infrastructure [7, 8]. These potential benefits suggest that it is important to increase the use of the bicycle as a mode of active transportation.

However, a full public health understanding requires attention be paid not only to long-term population health and environmental benefits of bicycling, but also to the factors that influence risk of injury and fatality. Bicyclists are vulnerable because they must frequently share the same infrastructure with motorized vehicles, and yet bicycles offer their users no physical protection in the event of a collision. In addition, the mass of a typical automobile is at least an order of magnitude greater than a bicycle plus its rider, and motorized vehicles have top speeds that are considerably faster than bicycles. As a result, bicycle riders who are involved in a collision or a fall are exposed to a much higher risk of injury compared to motor vehicle users (with the exception of motorcycle riders).

To date, most studies of cycling safety – especially in North America – have emphasized helmet design, regulation, and implementation to mitigate the severity of cycling injuries when a crash occurs [9, 10]. This is particularly true for children [11, 12]. Cyclists in many North American jurisdictions are required by law to use helmets, although this is not the case in most European countries. While helmets are effective in reducing the severity of head injuries, they do not address impacts to other parts of the body [13, 14]. More importantly, they do not prevent incidents from occurring in the first place [15], and legislating their use may even discourage cycling [16].

The built environment has been implicated as a major determinant of bicycling rate [17, 18] as well as bicycling safety (the subject of this review), but these relationships are complex. It is important to understand how the built environment affects bicycling safety because it presents an opportunity to prevent injuries by modifying transportation infrastructure. Infrastructure improvement meets several important conditions for successful injury prevention measures: (a) it is population based, rather than requiring initiative on the part of the individual; (b) it is passive, rather than requiring active participation; and (c) it is accomplished with a single action, rather than requiring repeated reinforcement [15].

In this paper we review the evidence on how different types of transportation infrastructure affect bicyclists' safety. This paper is organized as follows: first we provide an overview of bicycling safety and ridership. Next we offer definitions of, and alternative terminology for, the transportation infrastructure used by cyclists that might be expected to influence their safety. We describe our literature search methodology and the inclusion and exclusion criteria, and present the results of the search in two detailed tables. Table 2 describes studies that assess the safety of intersections for cyclists, and Table 3 describes studies related to straightaways (i.e., roads, lanes and paths). We conclude by discussing the findings of this review, critiquing the methodological approaches used, and offering recommendations for future research.

Ridership and Safety

North Americans remain less likely than Europeans to choose bicycle transport for either short or long trips. Data on the share of trips made by bicycle are not often directly comparable between jurisdictions owing to differences in the survey methods employed (e.g., sampling scheme, definition of a trip, etc.), but comparisons are typically justified by the inability of these methodological disparities to explain the substantial difference observed (e.g., about 1% of trips are made by cycling in North America, vs. an estimated 10% of trips in Belgium, Switzerland, Germany, Austria, Sweden, and Finland, and more than 20% of trips in Denmark and the Netherlands) [19]. Along with these lower cycling rates, there is also a higher risk of injury associated with cycling in North America: an analysis of traffic injuries indicated a 2 to 3 fold higher risk of death and an 8 to 30 fold higher risk of injury while cycling in the United States vs. Holland and Germany, using either of the traditional transportation denominators: per trip or per kilometer traveled [20]. While these comparisons underscore cycling injury risks, they also provide reason for optimism. If cycling is safer in European cities, it can be made safer in North America.

There are clearly bicycling safety and popularity “gaps” between (and within) Europe and North America [21]. In addition, there is an important safety gap between cyclists and other transport modes: cyclists are 7 to 70 times more likely to be injured, per trip or per kilometer traveled, than car occupants [20, 22]. It is likely that public perception of a lack of safety acts as a deterrent to cyclists in North America. In surveys asking about factors that affect the choice of cycling as a mode of transportation, concern about safety is one of the most frequently cited deterrents [23-28]. For example, in a survey of adults in the Vancouver metropolitan area, the following were among the top deterrents: the risk of injury from car-bike collisions; the risk from motorists who don't know how to drive safely near bicycles; motorized vehicles driving faster than 50 km/hr; and streets with a lot of car, bus, and truck traffic [26]. The good news is that there is evidence that perceived safety improvements in bicycle transportation have an aggregate elasticity value greater than one (i.e., a 10% increase in perceived safety results in greater than 10% increase in the share of people commuting by bicycle) [25].

Increased ridership rates may result in improved safety for cyclists: injury rates have been shown to decrease with increased cycling rates [29, 30]. The principle of “safety in numbers” is supported by studies of injury and ridership patterns in California, Australia, and Europe, as well as between cities and within cities over time. There are a number of potential explanations. Motor vehicle drivers may not expect cyclists when there are few of them on the roads, and thus make so-called “looked-but-failed-to-see” errors that can result in collisions [31]. When motorists and cyclists are unaccustomed to sharing the road, both parties may hold incorrect assumptions about what the other party will do [32]. Increased cycling rates may mean that more motorists also use bicycles as a mode of transport, making motorists more attuned to cyclists and their movements, and encouraging them to drive in a way that accounts for potential interactions [30]. Finally, a larger cycling population means stronger lobbying power for cycling resources.

Finally, it is worth considering long-term temporal trends in motor vehicle injuries. The injury rate from motor-vehicle crashes has steadily declined since the 1920s in many parts of the world, in part attributable to improvements in road-related infrastructure [33]. This provides reason for optimism: the risk of injury or death from traffic crashes is modifiable, and this is likely to extend to the infrastructural determinants of cycling injuries.

Safety and Infrastructure Terminology

Safety terminology

Bicycling safety is usually quantified by measuring one or more of the following metrics: (a) injuries; (b) crashes; and (c) “conflicts”. Injuries may be classified according to their type and severity using standardized methods such as the World Health Organization’s International Classification of Diseases [34] and the Association for the Advancement of

Automotive Medicine’s Abbreviated Injury Scale (AIS), and may include fatalities. Crashes can be classified as either a collision or a fall, where a collision is defined as an event in which the bicycle hits or is hit by any other object, regardless of fault, and a fall is an event (not caused by a collision) where the bicycle and/or bicyclist lands on the ground.

A conflict is normally defined as an interaction between a bicyclist and another road user such that at least one of the parties has to change speed or direction to avoid a collision. Types of conflict examined in bicycling safety studies include avoidance maneuvers at intersections [35-37], bicycle-motor vehicle interactions during passing events on roads, lanes, or paths [38-41], and “wrong side passing events” on shared-use paths [42]. Conflict studies may offer valuable insights into how cyclists and other road users behave during their interactions on various types of transportation infrastructure. However, it is unknown whether the safety of the cyclists was compromised during the conflict events. In addition, the conflict studies we identified were generally based on a small number of observed events, which were made over a limited time period (usually several hours), and often in a single geographical location. Therefore, papers that use conflict as their sole outcome measure have not been included in this review.

In the literature that examines traffic-related injuries and crashes (including many of the papers reviewed here) the word “accident” is frequently used, for example in the phrase *motor vehicle accident*. However it has been argued that the term “accident” implies that the event in question has happened entirely by chance, and is therefore unpredictable and unpreventable [43] as opposed to being a result of modifiable risk factors. The editors of the British Medical Journal have even gone as far as to ban the use of the term [44]. We have refrained from using the word "accident" in this review, instead using the more specific terms "incident", "injury", "crash", "collision" and "fall" as appropriate. However, we do indicate if the original study authors used the word accident to describe the outcome measure.

Infrastructure terminology

Key terms that describe transportation infrastructure used by cyclists are defined in Table 1. We have indicated if a given type of infrastructure has not been studied in the scientific literature identified by our search of the English-language literature.

Table 1. *Key terms that describe transportation infrastructure used by cyclists*

Methods

Search strategy

We searched the following bibliographic databases: *Pubmed* and *Medline*, which index over 3,600 international medical and health care journals (1949 to present); *Web of Science*, which includes the Science Citation Index, the Arts and Humanities Citation Index, and the Social Sciences Citation Index (1989 to present); and *Transportation Research Information Services*, which includes references to books, technical reports, conference proceedings and journal articles in the field of transportation (1960 to present). In order to identify relevant studies, we used search terms related to the safety of bicyclists, and to transportation infrastructure. Combinations of the following keywords were used in the searches, (with "wildcards" used where appropriate to capture variants on terms, e.g., bicycl*): bicycle, safety, injury, accident, crash, conflict, infrastructure, road, and intersection. Reference lists of all relevant papers including review papers were searched as a source of additional citations. The initial literature search was conducted in summer 2008 and updated through to June 2009.

Inclusion and exclusion criteria

All papers identified by the search were initially screened for relevance using the title and/or abstract. Specifically, we sought papers that met the description of injury epidemiology studies, injury severity studies, and crash/collision/fall rate studies, which considered some aspect of infrastructure as a determinant/predictor of bicyclists' safety. These included "before and after" studies that examine the safety impact (change in injury or crash rate for cyclists) of some infrastructural change. Those papers considered potentially relevant were collected from the University of British Columbia libraries, electronic databases maintained by the journals, or through inter-library loan. The full texts of the papers were then further reviewed for relevance.

Papers were considered relevant and included in the review if they met the following criteria:

- they investigated a relationship between transportation infrastructure (designed for either motorized or non-motorized use) and a clearly-defined metric of bicyclist safety (injury, injury severity, crash/collision/fall); and

- they were English-language publications describing empirical research conducted in an Organisation for Economic Co-operation and Development (OECD) country. For countries outside the OECD, it was expected that the transportation infrastructure and bicycling rates (as well as the socio-economic motivators of bicycling) would be different, and consequently the study results may not be applicable across regions. The literature search did not locate any relevant papers describing studies conducted outside the OECD.

We excluded papers from further review if they met any of the following criteria:

- studies of injuries or crashes that occurred when the bicycle was being used for bicycle racing, “off-road mountain-biking”, trick/trials riding, or play;
- studies only examining non-infrastructural determinants of safety such as helmet-use, bicycle type, personal characteristics of the bicyclists or motor vehicle driver (e.g., age, sex, experience);
- studies of injuries not related to a crash event, e.g., chronic injuries related to riding position;
- studies examining gross numbers/types of injuries in a region for a given time period, without either calculating rates (per exposure/riding time) or considering infrastructural determinants of those injuries;
- studies that reported only subjective perceptions of safety or risk, whether by lay-public or experts; and
- studies that examined only conflict between cyclists and other road users, such as motor vehicle encroachment into adjacent lanes or bike boxes, distance of motor

vehicle or bicycle from the curb, or “wrong-side” passing maneuvers on shared use bicycle paths.

Results

In total, 23 papers were identified that met the inclusion criteria. Eight examined infrastructure related to intersections, and are abstracted in detail in Table 2 [45-52]. Fifteen papers examined infrastructure related to “straightaways”, i.e., roads, lanes and/or paths, and are abstracted in Table 3 [13, 22, 53-65]. Studies are presented in the tables first by type of infrastructure, then by year for each type.

Table 2. *Studies that investigated relationships between bicyclist safety and intersection-related transportation infrastructure*

Table 3. *Studies that investigated relationships between bicyclist safety and transportation infrastructure related to roads, lanes and/or paths.*

Ten of the 23 studies reviewed used injuries (or both injuries and crashes) as a metric of bicyclist safety, four examined injury severity, and nine examined crashes (i.e., collisions and/or falls). Most of the studies were published since 1994, except three US studies which were published in the mid-70s [53, 54] and in 1988 [55]. All the study designs were observational. Five of the intersection-related papers [45, 48-51], but only one of the road/lane/path-related papers [55], were “before-after” studies that quantified the change in cyclist safety before and after some infrastructure-related intervention took place. The remaining papers were classified as “non-intervention” observational studies. Most of the studies based their analyses and conclusions on at least 150 observations of injury or crash events, and seven studies based their analyses on more than one thousand observations. However one study of roundabouts examined only 67 crashes, 58 of which resulted in injuries [46], and 2 non-intersection studies examined 87 and 89 crashes on roads with and without bicycle lanes [55], and on sidewalks versus roads [57] respectively.

Thirteen of the studies were published in public health related journals (mainly *Accident Analysis & Prevention* and the *Journal of Safety Research*), and nine were published in transportation engineering journals (mostly *Transportation Research Record*). The remaining study (on the safety of different road/lane/path infrastructure types) was conducted as part of a Master of Science thesis [53].

All but one of the studies about intersection-related infrastructure (Table 2) were conducted in European countries. Five of the European intersection-related studies examined the safety of roundabouts and two examined marked bicycle crossings. The non-European study examined how intersection design in Japan influenced number of bicycle-motor vehicle collisions [52]. Cyclists in Japan are required by law to travel on the sidewalk, so the results from this study may not be generalizable to countries with different traffic rules.

The findings of the roundabout studies show some consistency, with elevated risks for cyclists after installation of roundabouts with multiple traffic lanes or with on-road bike lanes, whereas there were risk reductions or no apparent increase in risk at roundabouts with separated bike paths [46, 48, 49]. One study showed a decreased risk for cyclists and moped riders after installation of roundabouts in the Netherlands [45], but the authors did not disaggregate the results for these two road-user groups. However, the finding from this study that roundabouts with separate cycle paths had a greater safety effect than those with on-road cycle lanes or no bicycle infrastructure is consistent with other research. Another study on roundabout safety in Flanders found a similar effect for "vulnerable road users" [66], but we have not included this study in our table because the vulnerable road user population included pedestrians and motorized two-wheeler riders as well as cyclists. It is evident that the safety effect of roundabouts, as measured in such "before-after" studies, is likely to greatly depend on the "before" configuration of the intersections in question.

The two studies of the safety effect of marked bicycle crossings at intersections looked at different design aspects (one on physically elevated crossings, one on coloring) and did not provide clear conclusions. Although the study on elevated crossings showed a small increase in the number crashes after the crossing was installed, the bicycle traffic volume grew by 50% more on the streets after the intervention, as compared to unchanged streets in the area, and this was not adjusted for in the analysis [50]. The second study showed a reduction in injury or crash risk when there was one colored bicycle crossing at an intersection, but an increase in injury or crash risk when there were two or more colored crossings [51].

Of studies examining infrastructure related to straightaways on roads, lanes and paths (Table 3), all but one were conducted in Canada or the US. The only European study in this category is very different in its focus: the safety effect of rural street lighting in the Netherlands [65]. Perhaps unsurprisingly, this study found that the presence of street lighting on rural roads reduced the rate of cyclists' injuries by half. The effect was corroborated by an injury severity study that found that crashes resulting in more severe injuries were significantly associated with unlit roads at night [61].

Most of the remaining studies in this category compared cyclist injury or crash rates on different types of road-related infrastructure that cyclists commonly travel, namely major and minor roads without specific cycling facilities, roads with wide curb lanes or marked cycle lanes, bicycle routes, off-road bike paths or mixed-use paths, and sidewalks. A difficulty with this literature was that facilities were grouped into categories (between 2 and 7 in number), such that facilities with potentially different risks were classified within a single category. In addition, the categorizations differed from study to study, and the terminology used was sometimes not clearly defined or consistently used. Despite these limitations, there are still some consistent messages.

On-road bike lanes were found to have a positive safety effect in five studies, consistently reducing injury rate, collision frequency or crash rates by about 50% compared to unmodified roadways [53, 54, 57-59]. Three of those studies [53, 58, 59] found a similar effect for bike routes. One study [55] found that there was an increase in crash rates in the year following installation of bike lanes on a major road, especially for a section counter to on-road traffic flow, but this effect was not sustained over the long term. None of the studies we reviewed examined bicycle “tracks”, the separated facilities commonly used next to major roads in countries such as the Netherlands and Denmark.

There is less consistent evidence about off-road riding, possibly because this category encompassed a wide variety of facility types. There may be confounding factors such as whether the surface was paved or unpaved, or for bicycles only or multiple user groups. Two studies examined off-road bike paths and found reduced risks, ranging from 0.11 to 0.67 times the risk of cycling on minor roads [56, 59]. Two studies that grouped paved and unpaved, bicycle only and multiuse urban trails in their off-road path category found elevated risks, 1.6 to 3.5 times higher than riding on-road [22, 58, 60]. Studies that examined unpaved off-road trails as a separate category found risks of injury 2.5 to 7.2 times higher than on-road cycling [53, 57].

Most studies that considered sidewalk-riding suggested that it is particularly hazardous for cyclists, with estimates of 1.8 to 16 times the risk of cycling on-road [22, 58-60, 63]. However one study found that the risk of traveling on the sidewalk was the same or lower than riding on residential streets [56]. Another considered the direction of travel and found that the elevated risk when sidewalk cyclists entered intersections was almost exclusively related to cycling against the flow of adjacent on-road traffic [63].

Four studies examined the association between various infrastructural characteristics and injury severity [13, 61, 62, 64]. More severe injuries were significantly associated with motor vehicle involvement, wider roads, perceptible road grades, and one-way streets. Injury severity does not reflect risk of an incident, but rather the outcome of the incident once it occurs. In comparison, the studies that examined injury or crash rates, as opposed to those that concentrated on injury severity, were our primary focus since we are most interested in shaping transportation infrastructure for injury prevention.

Discussion

In this review we have described two categories of infrastructure: the first related to intersections; and the second related to straightaways on roads, lanes and paths. It is of interest to note that studies of the former type of infrastructure were conducted almost entirely in Europe, while studies of the latter were conducted almost entirely in North America. The reason for this may be the substantial differences in urban form, existing cycling infrastructure, cycling rates, and even the culture of cycling between Europe and North America. Pucher and colleagues have discussed this issue extensively [19, 67]. There is also significant variety in infrastructure design from one country to another, and even within a given city. Despite this, our review has revealed that relatively few types of infrastructure have been studied. For example, some common types of infrastructure in North American cities have not been assessed: traffic circles; this includes bike boxes; “sharrows”; speed bumps/humps; and traffic diverters (refer to Table 1). One of the limitations of this review is that we have only included studies in the English scientific literature, although we are aware that there may be studies reported only in other (particularly European) languages.

The principal trend that emerges from the papers reviewed here is that clearly-marked, separated bike facilities (i.e. bike lanes and bike paths) are consistently shown to provide improved safety for cyclists compared to on-road cycling with traffic. On-road bike lanes and bike routes were found to reduce injury or crash rate by about half compared to unmodified roadways. This finding applies not only to straightaways but also to intersections with roundabouts, where it was found that separate cycle paths routing cyclists around an intersection separately from motor vehicles are much safer than on-road bike lanes or cycling with traffic. It has been suggested that the reason for high rates of bicycle-motor vehicle collisions at intersections is that motor vehicle drivers may be making “looked-but-failed-to-see” errors, whereby they search for oncoming motor vehicles but do not recognize that a cyclist is approaching because they are not looking for them [31].

Roundabouts may become more popular in North America than they are at present because of evidence that conversion of intersections to roundabouts reduces crash risk for motor vehicle road users by 30-50% [68], especially when they replace intersections that were not previously signal-controlled. However, because the cyclist-specific safety effect of roundabouts appears to be highly dependent on their design, transportation infrastructure planners should carefully consider interactions between cyclists and other traffic modes. A literature review on the safety effect of roundabouts, prepared for the

18th Workshop of the International Co-operation on Theories and Concepts in Traffic Safety (ICTCT), comes to similar conclusions [69]. It may be prudent to avoid installing roundabouts in areas where there is a high proportional volume of bicycle traffic, for example along designated bicycle routes on residential roads. In some North American cities there is retro-fitting of "traffic circles" at intersections in residential areas. Since these are quite different from the larger-diameter roundabouts found in Europe, their effect on cyclist safety should be investigated before more widespread use is advocated. The reviewed literature also confirms some things that may already be "common-sense" for transportation planners and safety experts: that streets used by cyclists at night should have good street-lighting, road surfaces should be paved and well-maintained, and bike routes should avoid excessive grades wherever possible.

An issue with the literature to date, especially that related to roads, lanes, and paths, is that some investigators did not define the terminology used. For example, the meaning of bike "paths" was not defined in the paper by Tinsworth et al. [56]. Other investigators clearly defined their infrastructure terms, but grouped facilities that may have different injury risks. For example, the studies of Aultman-Hall et al. [22, 60] defined paths as "an off-road (usually multi-use) paved or unpaved path or trail," grouping paths for bikes only, which were found by others to have lower risks than cycling on roads [56, 59], with unpaved trails, which were found by others to have higher risks [53, 57, 58]. Definitions of terminology are especially important in questionnaire-based studies to ensure that study participants are all answering with the same infrastructure in mind; photos can be helpful in this regard [26].

Clear and specific categorization is also vital to transportation planners and engineers, so they can distinguish sometimes subtle differences between successful and problematic design characteristics. One of the difficulties of the studies in the English literature to date is that the range of infrastructure studied is small compared to the range of configurations used between and within jurisdictions. Some examples are described above, but there are many other features that merit investigation: stop signs; numbers of roads intersecting; junctions such as driveways and lanes; cyclist lane of travel in relation to parked cars; surface features such as cobble stones or street-car tracks; traffic calming measures such as diverters or road humps; and road/lane/path curvature.

Underreporting of some events is an issue that is common to all studies of bicycle injuries and crashes. Many of the studies reviewed here rely on administrative data sources including hospital records [13, 54, 56], police reported accidents [46-53, 61-65], and national or city-maintained registries [45, 55], all of which are likely to miss less severe events. For example, one of the large surveys [59], which found that 9.8% of the respondents had had a crash in the last year, but only two in five crashes (38.2%) had been reported to police. Over half (56.6%) required medical attention, but only one in twenty crashes (5.5%) required admission to a hospital. This underreporting may create bias in infrastructure-specific risk calculations, since collisions involving motor vehicles may be more likely to be reported to police for insurance reasons and to hospitals because they are more severe, as compared to collisions that happen with non-motorized users (which may happen more frequently on off-street paths). Results of studies using these data sources should be interpreted as reflecting risk of severe events. Other studies in this review used data from cyclist surveys that may capture a wider range of crash types, including those that are less severe [22, 53, 57-60]. However, survey data will not capture events that resulted in fatalities or incapacitating brain injuries and, depending on the method of survey administration, may not capture individuals who no longer cycle following a crash [22, 60]. No single study design can overcome these reporting problems, thus the importance of looking for consistency of results across different designs.

A great challenge in studying cycling injuries is ensuring that comparisons control for the number of cyclists at risk (also called “exposure to risk”). The before-after studies reviewed here aimed to do this by comparing numbers of injuries on the same intersection or roadway prior to and post introduction of an infrastructure intervention, with the assumptions that underlying traffic levels, injury rates, and types of cyclists stay the same. These assumptions may not hold [50], so some of these studies also adjusted for temporal trends in traffic volumes [50, 51, 55] or injury rates in the area [45], or made additional comparisons to unchanged intersections [48-51]. The non-intervention studies needed to include methods to derive bicycling trip volumes on the infrastructure types being compared. Sometimes these came from administrative data collected by transportation authorities [46, 47, 52, 63, 65], and sometimes from study participants describing the route of an injury trip or their typical cycling location [22, 53, 56-60]. Injury severity studies made comparisons within the injured populations, so did not require trip volume denominators [13, 61, 62, 64], but this meant that they examined differences in severity of the outcome once in an injury event, not the original risk of the event itself.

Though the most basic requirement for studies examining risk of crashes or injuries is to account for exposure to risk, there are many other factors that may confound comparisons and that ideally would be controlled in study design or adjusted for in analyses. For example, men and women or people in different age groups may choose to cycle on different facility types, and might have different skill levels or risk-taking behavior, thus creating the potential for confounding associations between infrastructure and injury. While it is difficult to control for all potential confounders, many of the non-intervention studies reviewed here did adjust for personal factors such as age [13, 22, 56, 57, 62, 63], sex [22, 56, 57, 63], cycling experience [22, 60], bicycle type [57], and environmental factors such as time of day [56, 61, 62, 64, 65] and weather [57, 61, 62, 64]. Most injury severity studies adjusted for helmet use [13, 61, 64]. A style of observational study that can control for most potential confounders is the case-crossover design [70]. Such a study is underway in the Canadian cities of Toronto and Vancouver. It will compare infrastructure at the injury site to that of randomly selected control sites on the same trip, thus within-trip factors (including age, sex, cycling experience, propensity for risk taking, alcohol or drug use, bicycle type and condition, visibility via clothing or bicycle lights, weather, time of day, etc.) are controlled in the design.

Conclusions

This review highlights many opportunities for more detailed and controlled studies of infrastructure and cycling injuries, however the studies to date provide some guidance for improving cyclist safety. The evidence suggests that purpose-built bicycle-only facilities (e.g., bike lanes and paved off-road paths) reduce the risk of crashes and injuries for cyclists compared to cycling on-road, with traffic. At intersections, roundabouts are more hazardous to cyclists than other types of intersection unless separated bicycle paths are provided. Cycling on the sidewalk results in a significantly elevated risk of collision and injury. Street lighting, paved surfaces, and low-angled grades for cycling routes are additional factors that seem to improve cyclist safety.

The major advantage of improvements to infrastructure, compared to the current North American emphasis on helmet use, is that they provide population-wide, continuous primary prevention of injury events. Given the importance of cycling safety to decisions to cycle as a mode of transportation, and the importance of cycling modal share to the safety of cyclists, improvements to infrastructure based on the existing evidence have the opportunity to improve public health not only by preventing injuries and reducing their severity, but also via the ancillary benefits that accrue with this active and sustainable mode of transportation.

Competing Interests

The authors are part of a research team that is studying the association between bicyclists' injuries and the cycling environment in Vancouver and Toronto. The Heart and Stroke Foundation of Canada and the Canadian Institutes of Health Research have funded this three-year study. See http://www.cher.ubc.ca/cyclingincities/injury.html for more information.

Authors' contributions

KT, CR, AH and PC conceived of the study and developed the literature search strategy. CR, AH conducted the literature search. CR, AH, MW, and KT reviewed the included papers, and abstracted them for the detailed tables prepared for this paper. CR wrote the initial draft of the manuscript, and the other authors all contributed to its development, particularly the discussion. All authors reviewed and approved the final manuscript.

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Tables

Table 1. *Key terms that describe transportation infrastructure used by cyclists*

Term	Description
STRAIGHTAWAYS	
On-road cycling	When bicyclists ride on a roadway designed primarily for motor vehicles.

On-road bike route	Generally a residential road that is signed as being a “bike route”, and may have cyclist-friendly crossings on at major road-crossings, such as traffic signals with push-buttons that are easily operated by cyclists.
Bicycle lane	Part of the roadway marked with painted lines or a colored surface, to designate that they are reserved exclusively for cyclists. Bicycle lanes may terminate before an intersection, or continue through it.
Bicycle track *	Type of bicycle lane next to a major city street but separated by a curb or other physical barrier
Wide curb lane	The outer (curbside) lane of a multi-lane road is wider than the standard width and can accommodate cyclists, although there may not be any signs indicating this.
Shared-lane bicycle markings ("sharrows") *	Symbols painted on the roadway indicating that bicycles can share the lane with motor vehicles. They are sometimes used on roads with high cyclist traffic that don’t have enough width to accommodate a dedicated bicycle lane.
Off-road path	Paved or unpaved path or trail, which may be for bicycle-use only or shared with other non-motorized users (e.g. pedestrians, runners, or in-line skaters). The classification may include a wide variety of path types and designs, which may not be directly comparable each other.
Sidewalk	Paved walkway for pedestrian use, located by the side of road; they are known as “pavements” in some parts of the world (e.g., UK and Ireland).
Speed bumps/humps *	Raised ridge across the road designed to slow motor vehicle traffic (“traffic calming), particularly in residential areas. Speed humps are easier than speed bumps for cyclists to ride over because they are less steep-sided and more broad.
INTERSECTIONS	
Intersections	Where two or more roads either meet or cross at the same level.
Junctions *	May be road junctions (i.e., intersection), but the term is usually used to refer to the point where a laneway, path, or driveway meets a road.
Roundabout	Intersection of arterial streets with a central circle of sufficient diameter such that the road curvature accommodates all road vehicles, including trucks and buses. Roundabouts usually have splitter islands on the approaches, sidewalks around the edges, and crosswalks across the approaches set back from the intersection. Daniels et al. provide diagrams of different types of cycle facilities on roundabouts in the Netherlands [49]. Generally, entering traffic yields to traffic already in the intersection.
Traffic circle (or “rotary traffic island”) *	Raised concrete circles placed in the centre of minor street intersections; there are no splitter islands and the design vehicle is a passenger car.
Bicycle crossing	Distinct road crossings for cyclists that are sometimes raised or colored, and they may have cyclist-operated traffic signals.
Bicycle box *	A right-angle extension to a bike lane at the head of an intersection, which allows cyclists to wait at the head of the traffic queue on a red traffic signal and then proceed through the intersection ahead of motor vehicle traffic on green.
Traffic diverter *	Bike-permeable barriers that require motor vehicle traffic to turn instead of traveling straight ahead through an intersection, or that prevent motor vehicles from entering a street.

* These types of infrastructure were not examined in any of the studies identified for this review.

Table 2. *Studies that investigated relationships between bicyclist safety and intersection-related transportation infrastructure*

Table 3. *Studies that investigated relationships between bicyclist safety and transportation infrastructure related to roads, lanes and/or paths.*

[Note: Tables 2 and 3 are in landscape format, and have been submitted as separate files].

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Additional file 1: table 2 - intersection infrastructure (reynolds et al).doc, 55K
http://www.ehjournal.net/imedia/1399853885289161/supp1.doc
Additional file 2: table 3 - straightaway infrastructure (reynolds et al).doc, 83K
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