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Road lighting and cycling: A review of the academic literature and policy guidelines

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ABSTRACT

Many studies have explored the impact of macro and meso attributes of the built environment – such as population density, land use, proximity to services, and cycle infrastructure – on cycling. Less attention has been paid to micro attributes of the built environment. This paper reviews the academic literature on the relationship between road lighting and cycling, and identifies gaps to provide direction to future work. It also reviews policy guidelines on lighting and cycling infrastructure. Findings from the review of academic research show a clear positive effect of road lighting on cycling. The effect seems stronger among potential and less experienced cyclists. This suggests that investment in road lighting may be a cost-effective intervention to increase cycling and make it more inclusive. More empirical work is needed, including on the impact that lighting may have on different types of cyclists and cycling, the optimal lighting for cyclists, the cost-effectiveness of lighting interventions, and in developing countries and countries at extreme latitudes. There is also a need for research with higher geographic and temporal resolution, "before/after" approaches to explore changes over time, and accounting for other factors associated with cycling. Findings from the review of policy guidelines reveal that lighting in cycling infrastructure is increasingly being considered, not only for the safety of cyclists, but also to make utility cycling more appealing and accessible in the dark.

1. Introduction

Many studies have explored the impact of macro and meso attributes of the built environment – such as population density, land use, proximity to services, and cycle infrastructure – on cycling (e.g. Buehler and Pucher, 2012; Fraser and Lock, 2011; Winters et al., 2016). However, fewer have investigated micro attributes of the built environment such as road lighting, which may have a strong influence on people's choice to cycle at night.

Evidence shows that darkness discourages cycling (Fotios and Robbins, 2022; Fotios et al., 2019; Uttley and Fotios, 2017). This may be because, in the dark, cyclists and potential cyclists perceive a greater risk of crashing, due to reduced visibility to see hazards on their routes and to be seen by traffic. It could also be due to increased concern about crime and personal threats at night. The deterrent effect of darkness on cycling disproportionately affects women (Fotios et al., 2022; Heinen et al., 2011). This suggests that road lighting could provide reassurance and improve experiences of cycling in the dark, increasing cycling levels and making cycling safer and more equitable.

Previous literature reviews have touched on elements of the relationship between cycling and lighting. Fotios and Castleton (2017) reviewed lighting regulations and recommendations for cyclist safety in the UK, both relating to bicycle lighting and lighting of roads. Reynolds et al. (2009) reviewed the impact of transport infrastructure, including street lighting, on cycling collisions. Other reviews have looked at the associations between active travel or physical activity and environmental factors, including street lighting (e.g. Cerin et al., 2017; Prince et al., 2022). However, to the best of our knowledge, no academic paper has specifically reviewed the international academic literature on the relationship between road lighting and cycling.

This paper aims to (1) review the academic literature on the relationship between road lighting and cycling, and (2) identify research gaps to provide direction for future work. The academic review is guided by the following questions:

1. To what extent is road lighting associated with cycling?
2. What are the possible causes of this association?
3. Is this association the same between different groups?
4. How much lighting (and at what cost) is optimal for cycling?
5. How does lighting compare with other interventions to boost cycling?

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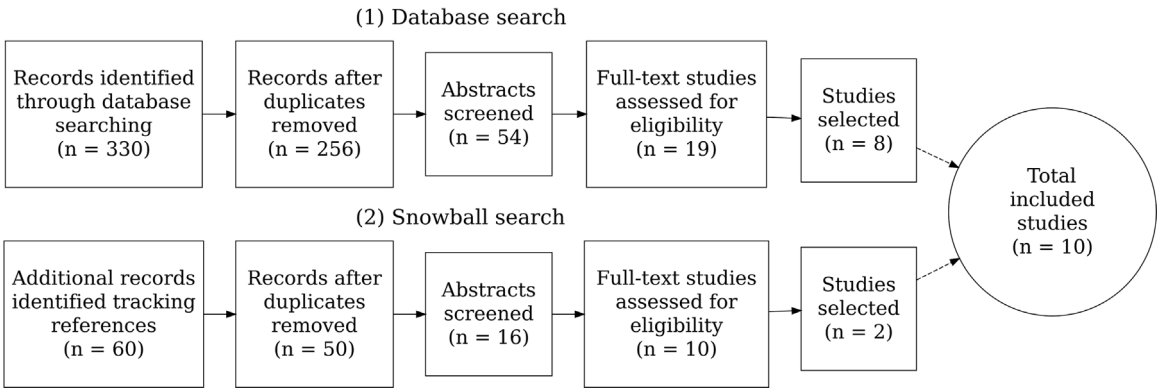

Fig. 1. Schematic showing the sampling strategy used to identify papers included in the review.

The paper also reviews updated policy guidelines on cycling infrastructure to examine the current state of guidance relating to lighting.

2. Methods

2.1. Academic literature review

2.1.1. Search strategy

We used a hybrid database and snowball search method. First, we searched in Scopus and Web of Science (WoS) databases, on 11 January 2023, for studies investigating the relationship between road lighting and cycling. For this, we used a query string that captured all the studies referring (in their title, abstract, or keywords) to lighting and cycling in different ways as follows:

> ("city light*" OR "public light*" OR "road light*" OR "street light*" or "city illumination" OR "public illumination" OR "road illumination" OR "street illumination" OR "city lamp*" OR "public lamp*" OR "road lamp*" OR "street lamp*" OR "lamp post*" OR "light post*" OR "light pole*") AND (bicycl* OR bik* OR cycling OR cyclist* OR "cycle hire").

This search resulted in an initial sample of 124 records from Scopus and 206 from WoS. After combining the search results (n = 330), excluding duplicates (n = 256), screening abstracts (n = 54), and assessing full texts for eligibility (n = 19), eight studies were selected.

Second, to make sure we did not miss any important studies, we tracked down the references (snowball search) from the studies selected in the database search (n = 60), and after excluding duplicates (n = 50), screening abstracts (n = 16), and assessing full texts for eligibility (n = 10), two additional papers were selected. In total, 10 studies were included in the review. A flow chart of the sampling strategy used to identify papers included in the review is shown in Fig. 1.

2.1.2. Inclusion criteria

Studies were included in the review if they (1) investigated the relationship between road lighting and cycling, (2) described empirical research, and (3) were peer-reviewed. By "road lighting", we meant outdoor lights that illuminate linear infrastructure on which people can cycle, including roads, dedicated cycleways, and shared usage walking/cycling paths. By "cycling", we meant cycling use (by cyclists or potential cyclists in survey-based studies), as well as any quantitative measure of cycling levels (in count-based studies) whether for transport, recreation, exercise, or sport.

We did not include studies that examined the association between darkness and cycling, or road lighting and cycling safety. Although these studies address topics very close to the one in this review, they are slightly different. Studies on darkness and cycling focus on how darkness (as a barrier) influences cycling, but not necessarily on how lighting (one of the solutions to darkness as a barrier) influences cycling. Studies on lighting and cycling safety focus on the effect of road lighting on the safety of cyclists, but not on the effect of road lighting on cycling use or levels.

2.1.3. Data extraction

From the included studies, we extracted the following information: author(s) and year, location, sample size, method (including analysis type and analytical tool), measurements (for cycling and road lighting), and result. A summary of this data extraction is presented in Table 1.

2.2. Policy guidelines review

We searched in Google search engine, on 17 November 2023, for relevant cycling infrastructure policy guidelines. The search was limited to documents published in English (or translated into English) by national government agencies or recognized professional transport planning organizations within the past ten years.

Eight relevant official guides on cycling infrastructure were identified. We evaluated them to understand whether and how they considered road lighting into cycling infrastructure. The following information was extracted from each of the guides: title, region, author (or organization or department responsible), year of publication, and a synopsis of their content regarding lighting. A summary of this data is shown in Table 2.

3. Results

3.1. Academic literature on road lighting and cycling

The academic literature on the relationship between road lighting and cycling is brief (only 10 studies met the inclusion criteria) and broadly spread across several disciplines, including engineering, public health, and urban design/planning. This highlights the little research to date on this topic and its multidisciplinary nature, and emphasizes the need for a synthesis of findings across disciplines.

All the studies reviewed were written in the last fifteen years and used quantitative methods. The first studies (conducted between 2008 and 2014) examined the association between road lighting and cycling using questionnaires (i.e. subjective measurements) and simple descriptive analyses. Subsequently (from 2015 to 2022), more advanced inferential studies were conducted, most of them using objective measurements and controlling for individual and environmental factors.

Most of the studies were conducted with population samples from cities and urban areas of North America (6), two from countries and cities of South America, one from a European city (Birmingham), and another from an Asian city (Beijing).

Table 1
Overview of papers on the association between road lighting and cycling.

Author(s)/year	Location	Sample size	Method		Measurements		Result
			Analysis type	Analytical tool	Cycling	Road lighting	
Lee and Moudon (2008)	Seattle and the surrounding urban areas in King County of Washington State (United States)	608 respondents randomly sampled, English speaking, 18 years or older, and able to walk	Descriptive	Descriptive statistics based on a telephone survey conducted in 2002.	Not applicable	Not applicable	"Good lighting at night" is the second most mentioned enabler of cycling, behind "continuous bike lanes/trails" but ahead of "bike racks at destinations" and other local environmental features.
Winters et al. (2011)	Metro Vancouver (Canada)	1,402 current and potential cyclists	Descriptive	Descriptive statistics based on a telephone and self-administered survey conducted in three seasonal waves in 2006.	Not applicable	Not applicable	"If the route is not well lit after-dark" is a major deterrent to cycling, especially for potential cyclists.
Sanders and Cooper (2013)	A major urban corridor in the East of San Francisco (United States)	537 survey participants intercepted on foot or bicycle at eight sites along the study corridor	Descriptive	Descriptive statistics based on an in-person survey conducted during a 2-week period in September 2010.	Not applicable	Not applicable	Increasing street lighting is the second top suggestions for cyclists to improve safety.
Segadilha and Sanches (2014)	São Carlos (Brazil)	49 frequent commuting bicycle users	Descriptive	Descriptive statistics based on a survey conducted between September and December 2013.	Not applicable	Not applicable	Street lighting and security are two of the main factors (5 and 6 out of 18) for cycle commuting routes after (1) number of trucks (2) buses (3) traffic volume and (4) speed.
Poorfakhraei and Rowangould (2015)	University of New Mexico, Albuquerque (United States)	161 students taking economics courses	Inferential	A stated preference survey was created and a random utility model used to estimate willingness to pay for cycle tracks, bicycle lanes, and street lighting.	Not applicable	Not applicable	Cycle tracks were valued the most, followed closely by street lighting and then bicycle lanes.
Chen et al. (2018)	Seattle (United States)	3,310 routes for 197 cyclists	Inferential	Route choice modelling and mixed logistic regression models	Cycling volumes along different route options	Street lights per mile in 50-ft buffers	Light density was found a significant predictor of bicycle route choice after bicycle lanes, slope, trip length, and speed limit.

(*continued on next page*)

Table 1 (*continued*).

Author(s)/year	Location	Sample size	Method		Measurements		Result
			Analysis type	Analytical tool	Cycling	Road lighting	
Fotios et al. (2019)	Arlington County (United States)	Pedestrian and cyclist counts from 11 counters in 2012, increasing to 32 counters by the end of 2015	Inferential	Changes in walking and cycling rates between daylight and after-dark were quantified by calculating an odds ratio. A comparison of these odds ratio was then made between lit and unlit locations.	Automated cyclist counts between January 2012 to December 2015 inclusive	Lit vs unlit counter locations	More people were found to walk on foot paths and cycle on cycle trails after dark when they were lit than when they were unlit.
Uttley et al. (2020)	Birmingham (United Kingdom)	Cyclist counts from 48 counters	Inferential	Changes in cycling rates between daylight and after-dark were quantified by calculating an odds ratio. These odds ratio were then compared against density of road lighting lanterns and relative brightness.	Automated cyclist counts between January 2012 to December 2015 inclusive	Lantern density and relative brightness as estimated from night-time aerial images dated 2016–12	The drop in cycling levels after dark was substantially greater in unlit locations, compared with lit locations.
Zacharias and Meng (2021)	Beijing (China)	3 million trip records in 661 street segments	Inferential	Linear regression models	Dockless bicycle uptake and deposit rates for a ten-day period in May 2017	Street segment lighted (0 = no, 1 = yes) from satellite imagery dated from 2017-05 to 2017-06	Street lighting was found strongly positively associated with dockless bicycle uptake and deposit rates.
Castillo-Paredes et al. (2022)	92 cities from 8 Latin American countries (Argentina, Brazil, Chile, Colombia, Costa Rica, Ecuador, Peru, and Venezuela)	8,547 adults between 18 and 65 years old	Inferential	Logistic and linear regression models	Cycling participation (people who cycled more than 10 min/week) and duration (average min/week cycling) based on the Latin American Nutrition and Health Study conducted between 2014-09 and 2015–02	Streets lighting perception based on the Latin American Nutrition and Health Study	No associations were found between the perception that streets are not well lit and cycling participation and duration.

3.1.1. Descriptive studies

Lee and Moudon (2008) examined the relationship between neighbourhood environments and walking and cycling, based on a 608-respondent telephone survey conducted in 2002 in the region of Seattle and the surrounding urban areas in King County of Washington State, US. They found that "good lighting at night" was the most mentioned environmental enabler of walking, and the second most mentioned enabler of cycling, behind "continuous bike lanes or bike trails" but ahead of "bike racks at destinations" and another micro feature of the local environment: trees along streets. They concluded that lighting represented a small intervention that could be implemented quickly to increase local active travel levels, alongside longer-term interventions to build environment variables such as "street layouts, zoning regulations, and land-use practices".

Winters et al. (2011) investigated motivators and deterrents of cycling, based on a survey of 1,402 current and potential cyclists in Metro Vancouver, Canada. They found that a major deterrent to cycling was "if the route was not well lit after dark". The effect of this deterrent was largest for people who don't currently cycle but potentially would do in the future (potential cyclists). The study highlights the importance of road lighting in enabling the uptake of cycling.

Sanders and Cooper (2013) conducted a study on the design preferences of pedestrians, drivers, cyclists, and public transport users in a major urban corridor in the East of San Francisco, US. Participants were intercepted "in a variety of locations along the street, including at intersections and bus stops, while entering or leaving local businesses, and midblock" during a 2-week period in September 2010. From 537 responses, increasing street lighting was the second most suggested intervention for improving cycling safety.

Segadilha and Sanches (2014) undertook a questionnaire-based survey in São Carlos, Brazil – a city with around 220,000 inhabitants at the time of the survey – to evaluate perceptions of factors that influence cycling route choice. Based on results from 49 frequent bicycle commuters, they reported that street lighting and security were two of the main factors (5 and 6 out of 18) affecting cycle commuting route choice, after number of trucks, number of buses, traffic volume, and speed.

Table 2
Overview of guides on cycling infrastructure regarding their reference to lighting.

Title	Region	Author	Year	Reference to lighting
Urban Bikeway Design Guide	North American region	National Association of City Transportation Officials (NACTO)	2014	No specific reference.
Separated Bike Lane Guide	United States	Federal Highway Administration (FHWA)	2015	No specific reference.
Design Manual Bicycle Traffic	The Netherlands	CROW-Platform	2016	Section on lighting (pp. 186–190) with two subsections: (1) lighting according to function (main cycle routes, basic network, recreational network); and (2) lighting related to location and usage (edge markings, cycle underpasses, luminance, colour and uniformity, dazzing, exclusively used bicycle connections).
Guide to Road Design. Part 6A, Paths for Walking and Cycling	Australia	Austroads	2017	Section on lighting (pp. 51–52) with a subsection on walking and cycling paths away from roads.
Cycle Infrastructure Design LTN-1-20	United Kingdom	Department for Transport	2020	Two sections on lighting: one in the chapter 'Motor traffic free routes' (p.88), and another in the chapter 'Construction and maintenance' (p.166).
Cycling by Design	Scotland, United Kingdom	Department Transport	2021	General consideration and section on lighting at crossings (p.154).
OTM Book 18	Ontario, Canada	Ontario Traffic Council	2021	Section on lighting (pp. 257–258) with a subsection on illumination levels.
Cycle Design Manual	Ireland	National Transport Authority	2023	Section on public lighting (pp. 162–164) with three subsections: (1) design objectives; (2) key issues to be considered (location of lighting columns, additional cycleway lighting, environmental impacts); and (3) design guidelines.

3.1.2. Inferential studies

Poorfakhraei and Rowangould (2015) estimated welfare change as willingness to pay (WTP) for three bicycle facility improvements: cycle tracks, cycle lanes, and street lighting. For this, they asked 161 students taking economics courses at the University of New Mexico in Albuquerque, US to choose between different levels of bicycle facility improvements and travel time, and also for their average and marginal wage rates. They found that street lighting was valued less than dedicated cycle tracks away from motor traffic, but substantially more than on road painted cycle lanes. They also found that cycling experience was associated with lower WTP for all the facility improvements considered. This study, based on a relatively small sample, cannot be assumed to be representative of the general population, but showed clear preferences for lighting among University of New Mexico's students.

Chen et al. (2018) examined the effects of built environment features, including street lighting, on cyclists' route preference. They used GPS data representing 3,310 routes made by 197 cyclists from Seattle, US, and a mixed logistic regression model. They found light density as a significant predictor of bicycle route choice. Its effect size was, however, lower than that of others predictors such as bike lanes, slope, distance travelled, and speed limit.

Fotios et al. (2019) analysed the impact of ambient light levels on walking and cycling. They examined an open access dataset from mobility (walking and cycling) counters at point locations next to linear segments of infrastructure in Arlington County, US. The input dataset provided counts for people cycling on "cycle trails, on-street cycle lanes and footpaths" continuously collected over 4 years "from 11 separate counters in 2012, increasing to 32 separate counters by the end of 2015". They found that more people walk or cycle during daylight than after dark, and more people cycle on cycle trails and walk on foot paths after dark if they are lit than if they are unlit.

Building on the findings of Fotios et al. (2019), Uttley et al. (2020) explored in more depth whether lighting can reduce the negative impact of darkness on cycling rates. Based on data from 48 cycle counters in Birmingham, UK, odds ratio calculated by Uttley et al. (2020) showed that locations with no road lighting had a significantly greater reduction in cycling after dark compared with locations with some lighting.

Zacharias and Meng (2021) explored associations between environmental conditions and dockless bicycle uptake and deposit based on 3 million trips in 661 street segments over a ten-day period in May 2017, in Beijing, China. Using regression models and lighting data from satellite and street view imagery, they found that street lighting was strongly positively associated with both dockless shared bicycle usage and deposit. Its effect size was found to be, however, smaller than that of other environmental conditions such as distance to the metro station, the presence of a dedicated bicycle pathway, street segment length, bicycle pathway maintenance, points of interest density, bicycle parking lots, and interruptions in the continuity of the bicycle lane for both dockless bicycle uptake and deposit.

Castillo-Paredes et al. (2022) examined the associations of perceived neighbourhood safety with active transport using a large survey containing responses from 8,547 adults between 18 and 65 years across 92 cities from 8 Latin American countries (Argentina, Brazil, Chile, Colombia, Costa Rica, Ecuador, Peru, and Venezuela). Results from logistic and linear regression models found an association between cycling participation and the perceptions of drivers exceeding the speed limit and unsafe crime rate during the day. They did not find, however, an association between the perception of streets being poorly lit and cycling participation and duration. Still, Castillo-Paredes et al. (2022) concluded that "variables related to crime, traffic speed, lack of safety in common spaces/green areas, and lighting of public spaces were associated with active travel in countries in Latin America".

3.2. Policy guidelines on road lighting for cycling

We identified eight relevant official guides on cycling infrastructure. They were published between 2014 and 2023 and from three different continents: North America (3), Europe (4), and Australia (1). All of them include recommendations on street lighting in bicycle infrastructure, except for the two oldest (least recently updated), which are the 2014 Urban Bikeway Design Guide of the National Association of City Transportation Officials (NACTO) (National Association of City Transportation Officials, 2014) and the 2015 Separated Bike Lane

Guide of the US Federal Highway Administration (Federal Highway Administration, 2015).

The Dutch Design Manual for Bicycle Traffic of the CROW-Platform (CROW, 2016) is the most detailed, with a specific section on lighting (pp. 186–190) divided into two subsections. The first subsection establishes that the main functions of lighting (in a cycle route) are to make the setting visible, enhance comfort, improve traffic flow and personal safety, and increase people's attentiveness and contrast between vehicle path and verge. The second subsection recommends lighting the main cycle routes, but not necessarily permanently if they are outside built-up area; considers lighting recreational cycle paths unnecessary; and states that specific lighting will be required where cycle routes diverge from the main carriageway, but not generally on cycle routes next to the main carriageway. It also recommends special attention to lighting at crossings and underpasses. Other issues addressed are luminance, colour and uniformity, dazzling, and lighting in extensively used bicycle connections.

The Australian Guide to Road Design (Part 6 A, Paths for Walking and Cycling) (Austroads, 2017) includes a section on lighting (pp. 51–52), which establishes that the main objectives of lighting are enabling perceived hazards and orientating, and enhancing personal security. These objectives, it indicates, "are particularly important for elderly people and people with impaired vision". It also determines that if paths away from highways are heavily used in the dark, their lighting should be considered, and that road lighting is indispensable in locations such as intersections, road crossings, underpasses, and tight curves. For lighting design, it refers to national standards.

The UK Cycle Infrastructure Design LTN-1-20 guide (Department for Transport, 2020) contains two subsections on lighting. The first subsection, in the chapter 'Motor traffic free routes' (p.88), suggests highway standard street lighting for off-carriageway routes. The second seubsection, in the chapter 'Construction and maintenance' (p.166), recommends lighting at subways and crossings, low light impact alternatives in cycle routes through large quiet parks or along canal towpaths, and no light in recreational routes outside build-up areas. For further guidance, it refers to (the UK charity) Sustrans, the Highways Act 1980 section 65(1), and the Technical Report 23 Lighting of Cycle Tracks (Institution of Lighting Engineers, 1998).

The lighting guidance provided by the Scottish manual (Transport Scotland and Sustrans, 2021) is concise, with a specific section on lighting at crossings (p.154). It recommends lighting "to ensure a high level of service for users at night" and considers it essential in underbridges and crossings. For further advice, it recommends looking at the Professional Lighting Guide 23: Lighting for Cycling Infrastructure (Institution of Lighting Professionals, 2020).

The Ontario Traffic Manual Book 18 (Cycling Facilities) (Ontario Traffic Council, 2021) includes a section on lighting (pp. 257–258), which estates that illumination should be provided for "all ages and abilities facilities, or those that are" key transport routes. It also indicates that lighting is especially important in underpasses, overpasses, and crossings; and not required in recreational facilities. A subsection on illumination levels provides details on the levels of horizontal and vertical illuminations. It also refers to a national standard for further design guidance.

Finally, the Cycle Design Manual from Ireland National Transport Authority (2023) presents a section on public lighting (pp. 162–164) divided into three subsections. The first subsection establishes that the objectives of lighting design are to illuminate the route ahead, the road surfaces, junctions, access and conflict points, and obstacles and other users. The second subsection indicates that lighting is essential in urban commuting routes, but not in outside built-up area routes for recreational purposes; that lighting is relevant to making cycling more inclusive; and that key issues are the location of lighting columns, additional lighting in off-carriageway lanes and on sudden bends or corners of cycle tracks, and the environmental impact of lighting. For design guidelines, the last subsection refers to general Irish codes of practice and guidance.

4. Discussion

4.1. Road lighting and cycling in the academic literature

4.1.1. A positive association

Nine of the ten studies reviewed in this paper found a positive relationship between road lighting and cycling. Specifically, all survey-based studies found road lighting as an important factor for cycling use (by cyclists or potential cyclists); and all except one count-based study found road lighting significantly positively associated with levels of cycling. This suggests that improvements in lighting conditions may be a relevant policy measure to encourage cycling in the dark.

One possible criticism of the general finding of a positive association between road lighting and cycling in count-based studies is that the routes with higher cycling rates may tend to be better lit. That is, we do not know to what extent cyclists prefer lit routes or routes are lit because they have more cyclists. Uttley et al. (2020) showed, however, no correlation between cycling volumes at the daylight control hour (as an indication of that route's popularity) and measures of how well lit those routes were.

There are before/after count-based studies in the literature on lighting and walking. However, they reached contrasting results. Atkins et al. (1991) found no changes in travel behaviour among neighbourhood residents after street lighting improvements. By contrast, Painter (1996) found that pedestrians activity increased significantly, in certain areas, after the introduction of lighting improvements. These contrasting findings could be explained by differences in the urban context (Appleyard and Ferrell, 2017; Ferrell and Mathur, 2012).

4.1.2. Possible causes of this positive association

Road lighting may help cyclists visualize their route and make them more visible and less at risk of being hit by motorized traffic during night trips. Research suggests that light conditions influence cycling crash risk and injury severity (e.g. Eluru et al., 2008; Uijtdewilligen et al., 2022; Yan et al., 2011). It may also provide reassurance against crime and personal threats. Although less investigated than the relationship between lighting and cycling collisions, there is evidence that street lighting decreases crime and enhances reassurance and confidence of pedestrians and cyclists after dark (e.g. Painter, 1996; Appleyard and Ferrell, 2017; Ferrell and Mathur, 2012).

Some of the studies reviewed in this paper also examined the relationship between crime and cycling. Winters et al. (2011) found "the risk of violent crime when cycling" as a deterrent to cycling. Sanders and Cooper (2013) reported "more police/less crime" as a street improvement requested to increase perceived traffic safe by pedestrians but not cyclists. Castillo-Paredes et al. (2022) found no association between "unsafe crime rate at night" and less walking or cycling participation and duration.

4.1.3. Variations by groups

The effect of road lighting on cycling may affect groups differently. Winters et al. (2011) found that poorly lit cycle paths after dark are more a major deterrent to potential cyclists than to current cyclists. This is supported, to some extent, by Poorfakhraei and Rowangould (2015) who found cycling experience associated with lower willingness to pay for improvements in urban cycling facilities, including street lighting. This suggests that improving lighting on cycle routes could be key to encouraging new people into cycling.

Segadilha and Sanches (2014) found no difference in the importance attributed to factors that influence cyclists' route choice (including street lighting) by gender, frequency of bicycle use, and age groups. However, there is evidence in the literature that women are more sensitive to dark spaces when walking and cycling than men (e.g. Fotios et al., 2022; Heinen et al., 2011; Sustrans, 2018; Xie and Spinney, 2018).

4.1.4. Optimal road lighting for cycling

Most of the studies reviewed in this paper are limited to analyse the association between road lighting and cycling, without examining to what extent this association varies by lighting quality or intensity. Uttley et al. (2020) is an exception. They looked at the effect of (1) density of road lighting lanterns and (2) relative brightness on cycling rates, and found "a non-linear relationship between relative brightness and the reduction in cyclists after dark". This suggests that a minimal amount of lighting may be enough to promote cycling at night.

Environmental policies increasingly promote energy-efficient and sustainable lighting systems to reduce energy costs and pollution. Smart street lighting systems, that is, public street lighting that adapts to the movement of road users, could be of great help in this regard. They could ensure that cyclists ride in well-lit areas, while areas with no detected activity remain dark – saving energy and preventing light pollution. Several articles on this topic came up while searching for studies for the academic review, such as Gagliardi et al. (2020), Juntunen et al. (2018), Savla et al. (2018), and Khatavkar et al. (2017).

4.1.5. Lighting and cycling in context

According to the studies reviewed in this paper, light is an important factor for cycling, but to what extent it is more or less effective than other factors to boost cycling? Lee and Moudon (2008) found lighting the second most mentioned enabler of cycling, behind continuous bike lanes but ahead of bike racks and other local environmental features. Sanders and Cooper (2013) found bike lanes more important than increasing street lighting. Segadilha and Sanches (2014) found motor vehicle speed and trucks in the flow volume more relevant than street lighting for cycle commuting routes. Chen et al. (2018) found street lights associated to bicycle route choice after bicycle lanes, slope, trip length, and speed limit; and Zacharias and Meng (2021) street lighting positively associated with dockless bicycle uptake and deposit, after bicycle pathway, bicycle pathway maintenance, and bicycle parking lots.

Still, the effectiveness of lighting on cycling is likely to vary depending on the location. For instance, in areas with high road traffic accidents and crime rates or at high latitudes such as Scandinavian countries, where darkness is a significant problem in winter, lighting is expected to be especially crucial. Also, it is important to consider the objective when determining the effectiveness of cycling interventions. Road lighting may not be very important in promoting cycling activity throughout the day; however, it may be key to reducing congestion during evening rush hours and making cycling more accessible after dark.

A wider consideration is that lighting is often part of a wider set of interventions with impacts on other uses of public space. Often, boosting cycling will not be the primary objective. From a policy perspective, it may be worth framing the impacts of lighting on cycling in the broader context of the impacts of lighting on other areas such as crime rates, local economic activity, and social cohesion.

4.2. Research gaps and future work

4.2.1. Empirical gaps

The findings highlight the following empirical research needs. First, a deeper understanding of how road lighting affects different types of cyclists and cycling is needed. Research suggests that the effect of road lighting is greater among potential cyclists (Winters et al., 2011) and less experienced cyclists (Poorfakhraei and Rowangould, 2015). However, we do not know how other sociodemographics such as gender, age, ethnicity, or income interact in this relationship. Also, more insight is needed into the type of cycling (e.g. transport cycling vs leisure cycling) that is most affected by road lighting.

Second, further research is needed into the intensity and type of road lighting that is optimal for cycling. We know that a minimal amount of lighting may be sufficient to boost cycling in the dark (Uttley et al., 2020), but more details on how road lighting for cycling should be is required. Also, does intelligent or "smart" street lighting reassure cyclists as traditional street lighting?

Third, more research in developing countries and countries in extreme latitudes is required. Three papers explored the relationships between lighting and cycling in developing cities in Brazil, China, and South America (Segadilha and Sanches, 2014; Zacharias and Meng, 2021; Castillo-Paredes et al., 2022). However, more research is needed in least-developed areas such as Sub-Saharan Africa. As highlighted by Mendiate et al. (2022), the "lack of street lighting (in Sub-Saharan Africa) can contribute to poor visibility, perception and fear of crime thus decreasing bicycle use". It would be also of interest to investigate whether there are differences in the impact of road lighting on cycling in countries with substantial periods of darkness during parts of the year.

Fourth, there is a need for research into lighting and cycling to be more explicitly policy relevant and, conversely, for design and policy guidance to account for the small but growing evidence base outlined in this paper. An example of this is the fact that none of the studies looked into the relative cost-effectiveness of lighting interventions compared with other common approaches to boosting cycling such as investment in new dedicated cycleways or road reallocation projects.

4.2.2. Methodological and data gaps

The literature review revealed several limitations in the methods and datasets used to assess the links between road lighting and cycling. First, the survey-based studies reviewed suffered from relatively small sample sizes. Only two of the six survey-based papers had sample sizes of at least 1,000 people (Castillo-Paredes et al., 2022; Winters et al., 2011). Papers based on cyclist counts had larger sample sizes (Fotios et al., 2019; Uttley et al., 2020). However, they were based on a few geographically distributed count points and lacked insight into the types of people and cycling that were most affected by lighting. This creates a need for research with a higher geographic and temporal resolution that provides insight into the types of people and cycling that benefit most from improved lighting.

Second, there is a lack of "before/after" studies that use longitudinal data to enable stronger conclusions about how lighting is not only associated with levels of cycling but change in levels of cycling. Such datasets could fit within a "natural experiment" framework to help understand the extent to which lighting can cause increases in cycling. The literature reviewed in this paper relies on exploring associations between road lighting and cycling, but provides no evidence of causality between changes in lighting and changes in cycling over time.

Third, the relationships between lighting and cycling in the literature were not always placed in the wider context of research on what works in terms of pro-cycling interventions. Given the wide range of factors that affect travel behaviour and mode choice, it is important to research cycling in the wider context of travel behaviour. Lighting is just one of multiple interacting factors that can affect cycling. Future research should include multiple explanatory variables including those found important in previous research (Fraser and Lock, 2011; Heinen et al., 2010; Wang et al., 2016; Winters et al., 2010), and account for feedback loops such as the "network effects" of high quality networks (Buehler and Dill, 2016).

A simple way to fill these gaps could be to include lighting as an additional variable in broader research into the causal factors that get people cycling. An advantage of adding lighting as an explanatory variable to existing or ongoing studies is that it could shed light on interaction effects that could provide answers to policy-relevant questions such as "is street lighting more effective when it is done in combination with measures to create wide, smooth, cohesive networks?" (our hypothesis: yes). A recent review into 'stick' policies to discourage driving and 'carrots', such as improved lighting (the topic of this review) and new cycling infrastructure, found that sticks may equally or even more important than carrots, especially when the two

policy types are done in combination (Xiao et al., 2022). This raises the wider question of whether lighting is more effective at increasing cycling in high traffic environments, in low traffic environments, or when undertaken alongside parallel measures to reduce car use. None of the studies reviewed addressed such wider questions, suggesting that future research into cycling and lighting should consider the wider range of options to not only increase cycling but to generate modal shift from motorised modes to active modes such as cycling.

4.3. Road lighting guidance in cycling policy documents

Despite the limited number of academic studies on road lighting and cycling identified in our search, most of the policy guides reviewed (six out of eight) provide recommendations on road lighting in cycling infrastructure to some extent. They consider it crucial for both road and personal safety, as well as for making cycling more attractive and inclusive at night; assuming, therefore, that proper lighting will lead to an increase in cycling levels and cycling diversity during dark hours. Most of the guidelines reviewed agree on four key themes regarding road lighting and cycling: (1) specific lighting is required where cycle routes diverge from the main carriageway, but not generally on cycle routes next to the main carriageway; (2) lighting for cycling is especially important through underpasses and at crossings; (3) recreational cycling facilities may not require full illumination (for environmental reasons); and (4) for further design guidance, national/regional standards should be consulted.

5. Conclusions

This paper reviews academic research on the association between road lighting and cycling and policy guidelines regarding cycling infrastructure lighting. Findings from the academic review show that, although the number of papers on the subject is still limited, there is sufficient evidence to conclude that road lighting is positively associated with cycling: nine of the ten studies reviewed found a positive relationship between road lighting and cycling. Several reasons could explain this positive association. Road lighting helps people who cycle better visualize their route and make them more visible to motorised traffic. It could also be because it reassures them against crime and personal threats in the dark. We also found that this positive association may be stronger among potential and less experienced cyclists. These findings suggest that investment in street lighting along segments with high potential for cycling (during dark hours) is likely to be an effective way to enable the uptake of cycling, specially among new and non-regular cyclists.

Empirical and methodological and data gaps were identified. More empirical work in cycling and road lighting is needed, including on the impact that road lighting may have on different types of cyclists and cycling, the optimal lighting for cyclists, the cost-effectiveness of lighting interventions, and in developing countries and countries at extreme latitudes. There is also a need for research with higher geographic and temporal resolution exploring the types of cyclists and cycling that benefit most from improved lighting, "before/after" approaches to explore changes in cycling over time, and accounting for other interacting factors associated with cycling.

Findings from the review of policy guidelines on road lighting and cycling reveal that lighting is increasingly being considered in the design of cycling infrastructure. Most of the reviewed guides empathise the importance of lighting for the safety of cyclists, but also to make utility cycling more appealing and accessible in the dark.

CRediT authorship contribution statement

Eugeni Vidal-Tortosa: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Robin Lovelace:** Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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