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Exposure measurement in bicycle safety analysis: A review of the literature

Jef Vanparijs[a], Luc Int Panis[b,c], Romain Meeusen[a,*], Bas de Geus[a]

[a] Department of Human Physiology, Faculty of Physical Education and Physical Therapy, Vrije Universiteit Brussel, Belgium
[b] Flemish Institute for Technological Research (VITO), Mol, Belgium
[c] Transportation Research Institute (IMOB), Hasselt University, Diepenbeek, Belgium

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ABSTRACT

Background: Cycling, as an active mode of transportation, has well-established health benefits. However, the safety of cyclists in traffic remains a major concern. In-depth studies of potential risk factors and safety outcomes are needed to ensure the most appropriate actions are taken to improve safety. However, the lack of reliable exposure data hinders meaningful analysis and interpretation. In this paper, we review the bicycle safety literature reporting different methods for measuring cycling exposure and discuss their findings.
Methods: A literature search identified studies on bicycle safety that included a description of how cycling exposure was measured, and what exposure units were used (e.g. distance, time, trips). Results were analyzed based on whether retrospective or prospective measurement of exposure was used, and whether safety outcomes controlled for exposure.
Results: We analyzed 20 papers. Retrospective studies were dominated by *major* bicycle accidents, whereas the prospective studies included *minor* and *major* bicycle accidents. Retrospective studies indicated higher incidence rates (IR) of accidents for men compared to women, and an increased risk of injury for cyclists aged 50 years or older. There was a lack of data for cyclists younger than 18 years. The risk of cycling accidents increased when riding in the dark. Wearing visible clothing or a helmet, or having more cycling experience did not reduce the risk of being involved in an accident. Better cyclist-driver awareness and more interaction between car driver and cyclists, and well maintained bicycle-specific infrastructure should improve bicycle safety.
Conclusion: The need to include exposure in bicycle safety research is increasingly recognized, but good exposure data are often lacking, which makes results hard to interpret and compare. Studies including exposure often use a retrospective research design, without including data on minor bicycle accidents, making it difficult to compare safety levels between age categories or against different types of infrastructure. Future research should focus more on children and adolescents, as this age group is a vulnerable population and is underrepresented in the existing literature.

1. Introduction

Cycling as an active mode of transportation holds the potential to reduce traffic congestion and air pollution, and promotes an active lifestyle which in turn improves public health (Andersen et al., 2000; Higgins, 2005; Mueller et al., 2015). The health benefits of active commuting by bicycle are well established (Mueller et al., 2015; de Geus et al., 2008, 2009; Oja et al., 2011). However, safety concerns may be a drawback, especially for children, adolescents and the elderly (Panter et al., 2010; Davison et al., 2008; Mindell et al., 2012; Maring and van Schagen, 1990; Martinez-Ruiz et al., 2014), age groups that incur more accidents than in adults (18–65 years) (Martensen, 2014). Cyclists often have to use the same infrastructure as cars, buses and trucks but are more vulnerable than the motorized road users as they are not protected by their vehicle in the case of an accident (Davis, 2001). Therefore, safety for cyclists must be improved if there is to be a modal shift from passive (motorized) transportation to active transportation.

To create a safer cycling environment, we need to understand where, when and under what circumstances bicycle accidents occur. When analyzing the literature, different methodological

* Corresponding author.
E-mail address: romain.meeusen@vub.ac.be (R. Meeusen).

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approaches are used. Some studies focus on injuries reported in hospital or police data (Dhillon, 2001; Boufous et al., 2011), some analyze the type of accidents (Meuleners et al., 2007; Keller et al., 2006; Boufous et al., 2013) and others analyze the relation between the built environment and infrastructure, and the occurrence of bicycle accidents (Dumbaugh, 2012; Harris et al., 2013). Regardless of methodological approaches, exposure data are needed for a better interpretation of the risk of being involved in a bicycle accident (Christie et al., 2007; Howarth, 1982; Roberts et al., 1997). An illustration of the need to take exposure into account comes from the study by Daniels et al. (2009). They concluded that "Roundabouts that are replacing signal-controlled intersections seem to have had a worse evolution on the number of bicycle accidents compared to roundabouts on other types of intersection" (Daniels et al., 2009). As the authors indicate, no correction for specific variations in traffic volume (exposure) was possible. If more people started using those roundabouts (increasing exposure) compared to signal-controlled intersections, the study conclusions may have been that the risk of being involved in a bicycle accident is statistically lower at those roundabouts. It is thus critical to take into account exposure when making decisions or producing bicycle safety guidelines based on such observations.

When evaluating bicycle safety, several independent factors should be considered. First, there is the 'demographic factor'. People of different ages, gender or socioeconomic status may need different traffic safety guidelines. The traffic situation and safety guidelines should be adapted to the users. For example, children cycling to school do not perceive the infrastructure in the same way as adults (Ghekiere et al., 2014; Timperio et al., 2004). Therefore, children may need different cycling infrastructure and safety guidelines compared to adults. A second factor that has an impact on cycling safety is the 'built environment' (Ewing and Dumbaugh, 2009). This includes 'infrastructure' and 'other traffic flows'. The level of safety of an infrastructural design depends not only on its users (a demographic factor) but also on traffic speed and density. A third factor is the 'the weather' and 'lighting conditions'. It is possible that winter and summer conditions produce different cycling outcomes. Traffic flow and lighting conditions also vary diurnally, as does the weather. Safety factors differ between a dark snowy winter day and a bright summer day. The final factor is the 'behavioral' factor. This factor describes behaviors in traffic such as wearing a helmet, the speed of cycling, listening to music or using a cell-phone. The transport mode and purpose of the trip are also variables. Since all these factors interact with each other, analyzing the safety of one factor should include controls for the other factors.

The aims of each study will determine the factors to be investigated. In addition to controlling for confounding factors, each factor should be controlled for at least one exposure unit in order to allow meaningful comparisons. Well-chosen exposure units should ensure that findings are robust, can be challenged and are consistent regardless of the scientific research paradigm applied (Stevenson, 2014). Comparisons can then be made between different studies using the same exposure units. In particular, the comparison of different infrastructural designs between countries may help to provide insights into improving bicycle facilities. Different countries show differences in cycling activity, built environments, infrastructure, travel behavior and age distribution, highlighting the importance of exposure reporting (Christie et al., 2007). Another advantage of consistently including exposure parameters in bicycle safety research is that it allows trends in exposure over time to be observed. This can be used to understand temporal trends in accident data, the consequences of policy interventions or the effect of new infrastructure on cycling safety. Several methodologies – each with advantages and disadvantages – have been developed to estimate or calculate bicycle exposure (Vandenbulcke et al., 2014).

The purpose of this review is to firstly examine the different methodological aspects related to measuring cycling exposure, and discuss their advantages and disadvantages. Secondly, the findings from the selected papers dealing with bicycling exposure will be discussed, with suggested approaches for future research.

2. Search strategy

We searched for papers related to bicycle accidents and exposure in four different databases: Pubmed, Web of Knowledge, ScienceDirect and Transport Research International Documentation (TRID). Only English language peer reviewed papers were included in this review. To identify relevant studies, the search terms used were bicycle, crash, accident, exposure, safety and infrastructure, including wild cards and in all possible combinations. Papers reporting any form of exposure measurement related to bicycle safety were included. Papers that did not measure exposure directly but estimated it using mathematical models were excluded. Only papers dealing with 'utilitarian cycling' (defined as 'commuting to or from work' or 'cycling to other destinations') were considered. 'Leisure' and 'sports-related' cycling (e.g. road cycling for competition or mountain biking) papers were excluded. The initial literature search was conducted in spring 2014 and had an outcome of 1578 hits. After the first screening for relevant titles and/or abstracts, 27 papers remained. The bibliographies of these 27 papers were scrutinized, resulting in the inclusion of 8 additional papers. The full texts of the 35 included papers were reviewed for relevance. Twenty papers (2% of the initial search) were retained for further analysis (Table 1).

3. Methodology and study design

3.1. Methods used to collect accident data

Studies of bicycle safety that report exposure data require two data categories, one for the exposure parameters (denominator) and the other for accident data (numerator). Several approaches may be used to collect accident data. First, both data categories (numerator and denominator) may come from the same cohort. Selecting cyclists involved in an accident through official accident registrations (e.g. hospital or police data) and asking for their exposure parameters is a possible approach. However, this would not necessarily represent bicycle exposure of the actual population or infrastructure, because people not involved in accidents are not taken into account. This would miss cyclists who demonstrate factors leading to safe bicycling, for example the choice of safer routes or taking better safety precautions than accident victims. This limitation can be overcome by including matched controls from a population not involved in an accident, but this increases the scope of a study.

Another possibility is combining data from official accident registrations with exposure data from national statistics. This includes cyclists who have not been involved in an accident. However, the exposure and accident cohorts are not matched. Another drawback is the incompleteness of official accident registrations. Only 7.1% of the incidents observed by de Geus et al. (2012) were also registered by police. A third approach overcomes these weaknesses by including a single, more general cycling population for accident and exposure data collection, even though respondents may not (yet) have been involved in an accident.

The follow-up study design includes a general cycling population and uses the same cohort for exposure and accident data. This includes cyclists that are not involved in bicycle accidents and thus