Accident Analysis and Prevention 62 (2014) 341–357

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Predicting cycling accident risk in Brussels: A spatial case–control approach

Grégory Vandenbulcke[a], Isabelle Thomas[a,b,*], Luc Int Panis[c,d]

[a] Center for Operations Research and Econometrics (CORE), Université catholique de Louvain (UCL), 34 Voie du Roman Pays, Louvain-la-Neuve B-1348, Belgium
[b] National Fund for Scientific Research (FRS-FNRS), Belgium
[c] Flemish Institute for Technological Research (VITO), Physical Activity and Activity Based Research on Exposure (PHA^{2}RE), Vlasmeer 7, Mol B-2400, Belgium
[d] Transportation Research Institute (IMOB), Universiteit Hasselt (UH), Agoralaan, Diepenbeek B-3590, Belgium

ARTICLE INFO

Article history:
Received 12 November 2012
Received in revised form 28 June 2013
Accepted 1 July 2013

Keywords:
Bicycle accident
Accident risk
Bayesian framework
Case–control strategy
Risk factors
Cycling

ABSTRACT

This paper aims at predicting cycling accident risk for an entire network and identifying how road infrastructure influences cycling safety in the Brussels-Capital Region (Belgium). A spatial Bayesian modelling approach is proposed using a binary dependent variable (accident, no accident at location *i*) constructed from a case–control strategy. Control sites are sampled along the 'bikeable' road network in function of the potential bicycle traffic transiting in each ward. Risk factors are limited to infrastructure, traffic and environmental characteristics.

Results suggest that a high risk is statistically associated with the presence of on-road tram tracks, bridges without cycling facility, complex intersections, proximity to shopping centres or garages, and busy van and truck traffic. Cycle facilities built at intersections and parked vehicles located next to separated cycle facilities are also associated with an increased risk, whereas contraflow cycling is associated with a reduced risk. The cycling accident risk is far from being negligible in points where there is actually no reported cycling accident but where they are yet expected to occur. Hence, mapping predicted accident risks provides planners and policy makers with a useful tool for accurately locating places with a high potential risk even before accidents actually happen. This also provides comprehensible information for orienting cyclists to the safest routes in Brussels.

1. Introduction

Bicycle use is nowadays promoted by public health and transportation specialists as an effective way to induce a shift to a healthier and environmentally sustainable lifestyle (Buehler et al., 2011; Chapman, 2007; de Nazelle et al., 2011; Elvik, 2009; Jacobsen, 2003; Polis, 2012; Vandenbulcke et al., 2009; WHO, 2002), even if there are adverse health effects due to the exposure to traffic exhaust or accidents (see e.g. Aertsens et al., 2010; Int Panis et al., 2010; Rojas-Rueda et al., 2011; Bos et al., 2013). There is a wide consensus that these risks are dwarfed by health benefits (de Hartog et al., 2010; Rabl and de Nazelle, 2011).

The risk of accident discourages people from cycling (McClintock and Cleary, 1996; Pucher et al., 1999; Parkin et al., 2007; Winters et al., 2011). Except in some countries benefiting from the 'safety in numbers' effect, the risk for a cyclist to be injured in a road accident is high, compared to motorists (Reynolds et al., 2009). Unfortunately, the risk and consequences of (minor) bicycle accidents are poorly known (Aertsens et al., 2010; Int Panis, 2011; Rabl and de Nazelle, 2011). There is hence the necessity to monitor minor bicycle accidents and to study the risk factors, so that policies can be devised to maximise the health benefits.

In this paper, we aim at: (1) predicting cycling accident risk for a whole network, and (2) identifying how road infrastructure influences cycling safety in the Brussels-Capital Region (Belgium). Within this framework, autocorrelation and multicollinearity are controlled using adequate statistical methods. From a methodological point of view, accident data are coupled with control points that are sampled along the road network, proportionally to an estimation of the bicycle traffic.

This paper is organised as follows. Section 2 presents an overview of the literature into traffic accident research. Section 3 defines preliminary concepts, describes the models and motivates the use of a case–control strategy. Section 4 presents the studied area and provides some figures in terms of bicycle use and accident risks for cyclists. Section 5 describes the data used within the

* Corresponding author at: Center for Operations Research and Econometrics (CORE), Université catholique de Louvain (UCL), 34 Voie du Roman Pays, Louvain-la-Neuve B-1348, Belgium. Tel.: +32 10 47 21 36.
E-mail address: isabelle.thomas@uclouvain.be (I. Thomas).

0001-4575/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aap.2013.07.001

modelling approach. Finally, Section 6 reports the main results that are further discussed and lead to recommendations in Section 7.

2. Overview of the literature into traffic accident research

2.1. Traffic accident research in general

Road accidents generally result from the combination and interaction between five categories of factors: human factors (e.g. driver behaviour), vehicle-related factors (e.g. size or state of the vehicle), infrastructure factors (e.g. crossroad design), traffic conditions (e.g. density of traffic) and environmental factors (e.g. weather) (Miaou et al., 2003; Li et al., 2007). Although considerable methodological improvements have been achieved in accident research during the last decades, the lack of information about the human factors, accident mechanisms and driver-related privacy issues have often hampered researchers to get in-depth knowledge about the exact cause and effect relationships with regard to the road accidents as a whole (Lord and Mannering, 2010). The body of the literature hence mainly focuses on examining the factors that affect either the *frequency* or the *severity* of accidents. Other studies investigate the association between the type of *collision* (e.g. rear-end accidents) and factors related to the accident mechanisms (Noland and Quddus, 2004; Lord and Mannering, 2010).

From a methodological point of view, much of the research into traffic accidents may be broadly classified into two groups, depending on the purpose of the study. First, *exploratory methods* may be used as an initial step to 'look at' the data, before performing explanatory methods. They aim at describing the accident data set using basic statistics (i.e. descriptive statistics, test statistics, odds ratios, etc.) and/or various spatial approaches (see e.g. Bailey and Gatrell, 1995; Levine et al., 1995a; Fotheringham et al., 2000; Myint, 2008; Shiode, 2008; Okabe et al., 2009). Second, *explanatory models* are commonly used to estimate the relative importance several factors may have on the occurrence and severity of accidents. Overall, three types of models are generally identified in the literature: the accident-frequency models, the accident-collision models and the accident-severity models. Concretely, the first category of model is applied to compute the probability of observing a definite number of accidents as a function of a set of factors (see e.g. negative-binomial models), while the second and third types of model focus on estimating the probability an accident falls into one definite class of collision or injury severity respectively (see e.g. multinomial or ordered logit models) (Ye and Lord, 2011). See Lord and Mannering (2010) for further information about accident-frequency models.

2.2. Focus on cycling accident research and relevant infrastructure factors

Much of the empirical work is recent (90s) and is mainly conducted in social sciences, medical and health care research and transportation (including traffic accident analysis, injury prevention, transport geography and engineering) (see Eluru et al., 2008; Reynolds et al., 2009 for a review of the literature). Examples of accident-frequency models applied to cycling accidents can be found in Wang and Nihan (2004), Hels and Orozova-Bekkevold (2007) and Schepers et al. (2011). On the other hand, empirical works aiming at comparing the impact of factors on different levels of injury severity for cyclists are far more common and can be found notably in Rodgers (1997), Klop and Khattak (1999), Kim et al. (2007) and Eluru et al. (2008). As regards accident-collision models, much of the work is – to our knowledge – quite recent and mainly aims at finding associations between the type of collision/manoeuvre (e.g. door-related and rear-end accidents) and a set of factors. Relevant examples can be found in Pai (2011) and Yan et al. (2011).

Focusing on the impact of road infrastructures, most of the studies found that the risk of having a cycling accident can be influenced by the road environment as well as by close facilities. In particular, *intersections* are generally known as black spots for cyclists as well as for all road users (Wang and Nihan, 2004; ERSO, 2006; Quddus, 2008; BRSI, 2009a,b; Reynolds et al., 2009; Haque et al., 2010; Pei et al., 2010). They are places where the number of potential conflict points and the risk of having an accident are higher compared to the rest of the network (Wang and Nihan, 2004; Dumbaugh and Rae, 2009). In particular, signalised intersections may lead to an increased risk of slight injury for cyclists, although they are generally associated with reduced risks of being fatally or seriously injured when cycling. At the opposite of the effects observed for other types of road users, roundabouts are also mentioned as having an unfavourable effect on cyclist safety, leading to an increased risk of accident when they replace other types of intersections (Hels and Orozova-Bekkevold, 2007; Daniels et al., 2008, 2009; Møller and Hels, 2008; Reynolds et al., 2009). This effect is even worse when the roundabout replaces a signalised intersection, or when marked bicycle lanes are used instead of other design types (e.g. mixed traffic or grade-separated cycle lanes) (Daniels et al., 2009).

The number and risk of bicycle accidents are generally influenced by the *traffic conditions* (i.e. traffic composition, flows/volumes, etc.) observed at the time of the accident (see e.g. McClintock and Cleary, 1996; Klop and Khattak, 1999; Wang and Nihan, 2004; Hels and Orozova-Bekkevold, 2007; Kim et al., 2007; Eluru et al., 2008; Anderson, 2009). During peak hours, congestion increases not only the number and the risk of non-fatal accidents for cyclists but also the perception of danger (Parkin et al., 2007; Hels and Orozova-Bekkevold, 2007; Møller and Hels, 2008), mainly because of the increased complexity of the traffic situation, the more aggressive driving behaviour and the restricted space left to the cyclists (McClintock and Cleary, 1996; Li et al., 2007; Wang et al., 2009). It however decreases the risk of being seriously or fatally injured in a road accident, owing to a reduced speed differential between slow and fast transport modes (Klop and Khattak, 1999). During off-peak hours, the opposite situation is observed: high vehicle speeds may be achieved, hence increasing the risk of being seriously or fatally injured for cyclists (Klop and Khattak, 1999; Hels and Orozova-Bekkevold, 2007; Kim et al., 2007; Eluru et al., 2008). For example, Kim et al. (2007) found a more than 11-fold increase in the probability of fatal injury as the estimated vehicle speeds pass 65 km/h. The *type of collision partner* (e.g. car user) also plays a key role in the severity of the accident. Depending on their speed, dimension and weight, they may lead to different injury severities. Cars generally account for the largest share of vehicles colliding with cyclists and cause most of injuries for these latter (ERSO, 2006; Chong et al., 2010; Loo and Tsui, 2010), while lorries, buses, vans and sports utility vehicles are more frequently involved in serious and fatal cycling accidents (McCarthy and Gilbert, 1996; ERSO, 2006; Kim et al., 2007; Eluru et al., 2008; BRSI, 2009a; Pei et al., 2010; Yan et al., 2011).

Although there is no consensus about the actual safety effects of the *cycle facilities*, the findings in the literature overall show that it is safer to cycle on-road than on fully segregated cycle facilities (or off-road facilities) (Forester, 1994; Rodgers, 1997; Räsänen and Summala, 1998; Aultman-Hall and Hall, 1998; Aultman-Hall and Kaltenecker, 1999; Pucher et al., 1999; ERSO, 2006). Throughout their review on the safety of urban cycle facilities, Thomas and DeRobertis (2013) also concluded that unidirectional cycle facilities are generally safer than bidirectional cycle facilities at intersections, and that cycle facilities with effective intersection treatments reduce accidents and injuries on busy streets. Regarding *discontinuities in the bicycle network*, Krizek and Roland (2005) found they