THE RISK FACTORS ASSOCIATED WITH BICYCLE CRASH SEVERITY: EVIDENCE FROM DENMARK

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ABSTRACT

In Denmark, cycling trips constitute a large share of the total trips and cycling safety assumes a top priority position in the agenda of policy makers. The current study sheds light on the risk factors associated with cyclist injury severity on Danish roads by examining a comprehensive set of accidents involving a cyclist and a third party between 2007 and 2011 and estimating a generalized ordered logit model of the severity of cyclist injuries. Model estimates and average pseudo-elasticities illustrate that cyclist injury severity is positively related to (i) cyclists over 60 years of age, (ii) cyclist intoxication, (iii) conflicts between cyclists going straight or turning left and other vehicles going straight, (iv) speed limits above 70-80 km/h, (v) slippery road surface, (vi) road sections, and (vii) heavy vehicle involvement. Moreover, model results show that cyclist injury severity is negatively related to (i) helmet use, (ii) the availability of cycling paths, (iii) dense urban development, possibly due to the 'safety in numbers' phenomenon.

Keywords: cycling accidents; injury severity; cyclist behaviour; generalized ordered logit.

INTRODUCTION

The last decade has witnessed a growing interest in developing strategies for cycling friendly cities among transport planners and regional policy makers across the U.S., Canada, Europe, Australia and South America. This interest stems from cycling bearing the potential of reducing congestion, air pollution and noise pollution from the societal perspective, while providing a healthy, affordable and enjoyable door-to-door transport option from the individual perspective (e.g., Pucher et al., 2010, 2011a, 2011b). As cycling policies are in development and cyclist numbers are on the rise, a renewed interest in the safety of cyclists is emerging. The relevance of the safety of cyclists is four-fold.

Firstly, safety concerns have been long recognized as a prominent barrier to the decision to cycle by non-cyclists or occasional cyclists in cities with low cycling tradition. For example, 47% of 3,000 respondents to an attitudinal survey in Madrid stated that accident risk was fundamental in their judgment about whether to cycle (Rondinella et al., 2012), and 21% of respondents in an attitudinal survey in Dublin mentioned that perceived risk was crucial in their decision not to switch from car to bicycle (Lawson et al., 2013).

Secondly, conflicts and near-miss accidents between cyclists and other road users have been frequently self-reported in cities with a consolidated cycling tradition. Near-miss accidents were measured at 0.18 events per mile in Oxford for pedestrians and cyclists, against 0.02 events per mile for car drivers, and were mentioned to be emotionally stressful (Joshi et al., 2001). Near-miss accidents were recounted by 43.5% of a thousand cyclists interviewed while approaching a roundabout in Copenhagen, against 4.6% actually being involved in collisions in the same location (Møller and Hels, 2008). Similar proportions of near-miss (27.8%) versus actual accidents (9.2%) were reported by cyclists in Queensland (Wood et al., 2009).

Thirdly, societal costs of cycling accidents are far from negligible. In Belgium, the annual costs of minor bicycle accidents were estimated in roughly 183 million Euros (Aertsens et al., 2010). In Denmark, when accounting for both direct (i.e., expenditure for police, rescue, medical care) and indirect (i.e., welfare loss from loss of life, quality of life reduction and net production loss) costs, the cost of bicycle injuries is approximately 60,000 Euros for a light injury, 400,000 Euros for a severe injury and 2.8 million Euros for a fatality.

Last, societal issues emerge when considering that vulnerable groups constitute an important share of cyclists. Children and adolescents have the highest rates of cycling in both the U.S. and Europe, while elderly reach 12% in Denmark and Germany and 24% in the Netherlands (Pucher and Buehler, 2008). Women have varying rates of cycling between 21% in Australia and 45-55% in Denmark, Germany and the Netherlands (Pucher and Buehler, 2008). Low-income immigrants living in dense urban areas in the U.S. cycle three times more than the average cycling rate (Smart, 2010).

The relevance of the safety of cyclists is reflected in the increasing number of recent studies, mainly focusing on accident and injury rates.

A major research stream investigated the effect of cyclists' behaviour on accident and injury rates, with particular attention devoted to helmet use and intoxication. The effect of bicycle helmet laws on head injury risks was explored in Australia (Robinson, 1996) and New Zealand (Robinson, 2001). The effectiveness of helmet use in reducing the risk of injuries was analysed in Taipei for children (Wang et al., 2009) and in Norway for different age groups (Kopjar and Wickizer, 2000). Elvik (2011) performed a meta-analysis of studies focusing on the effect of helmet use on head injuries. Intoxication among cyclists was examined in relation to injury risk in general (e.g., Olkkonen and Honkanen, 1990) and head injury risk in particular (Crocker et al., 2010, 2012), and intoxicated cyclists were found significantly different from sober ones in terms of risky behaviour and helmet use (e.g., Andersson and Bunketorp, 2002; Crocker et al., 2010, 2012). Recently, the effect of listening to music and using the cell phone on cycling speed and perception was investigated (de Waard et al., 2011).

Another prominent research line focused on the effect of infrastructure on accident and injury rates of cyclists. The safety consequences of cycle paths that pass continuously through intersections was investigated in Scandinavia (Gårder et al., 1994), and the road user adaptation leading to a decrease in time of the occurrence of bicycle-vehicle conflicts at intersections was studied in Norway (Phillips et al., 2011). Rates of bicycle-vehicle accidents were related to road geometry and traffic control at signalized intersections in Japan (Wang and Nihan, 2004), non-signalized intersections in The Netherlands (Schepers et al., 2011), and roundabouts in Denmark (Hels and Orozova-Bekkevold, 2007).

Another relevant research stream concentrated on accident and injury rates of cycling commuters. Accident rates, exposure by location, distance travelled per capita, type of accident, bicycle facilities, persons involved and circumstances were analysed from collision data in Canada (Yiannakoulias et al., 2012), as well as self-reports in Canada (Aultman-Hall and Hall, 1998; Aultman-Hall and Kaltenecker, 1999) and Belgium (de Geus et al., 2012).

Last, a minor research line focused on relatively rare accident types, such as cyclist-pedestrian collisions in Germany (Graw and König, 2002) and California (Zhang et al., 2012).

While the body of research regarding accident and injury rates is ample, the studies focusing on cyclist injury severity are scarce. Klop and Khattak (1999) estimated an ordered probit model to investigate the effects of road geometry, traffic volume, speed limit, and light and weather conditions on bicycle-vehicle accidents during the period 1990-1993. Kim et al. (2007) estimated a multinomial logit model to examine the effect of bicycle characteristics, driver characteristics, vehicle type and speed, collision manner, road geometry, land-use type, light and weather conditions in bicycle-vehicle accidents during the period 1997-2002. Both studies were conducted in North Carolina, a state with extremely low level of cycling where only about 0.2% of the commuting trips are cycling trips (Pucher et al., 2011a). Both studies were limited in scope, with the first focusing only on accidents on two-lane undivided roadways and the second concentrating only on accidents involving a bicycle and a motor vehicle. Recently, Bíl et al. (2010) investigated cyclist injury severity in the Czech Republic by estimating a logistic regression between severe and fatal injuries. The study is limited in both scope, since the focus is only on adult cyclists colliding against motor vehicles, and explanatory variables, since the focus is only on the pre-crash maneuvers of the party at fault.

The current study proposes a comprehensive analysis of the risk factors associated with injury severity of cyclists in Denmark. Denmark is one of the leading cycling nations, with 12,405 kilometres of cycling routes (58.3% are segregated paths) and 17% of cycling trips among the total trips (DTU Transport, 2012). The international relevance of the analysis of the risk factors associated with cyclist injury severity in Denmark is twofold. Firstly, analysing injury severity in a nation with high cycling mode share relates to the role of Denmark (but also Germany and the Netherlands) as an outer marker for future scenarios of realization of cycling potential in other countries (see, e.g., Pucher and Buehler, 2008). Secondly, the safety of cyclists in Denmark is a top priority issue considered in cycling strategies designed at the national and municipal level.

The analysis focuses on a comprehensive set of accidents involving a bicycle and a third party in Denmark during the period 2007-2011. The dataset details accident location, infrastructure characteristics and land use, light and weather conditions, cyclist attributes, behaviour and maneuvers, and characteristics of the collision partner. The dataset allows analysing cyclist injury severity at a national level, accounting for accidents involving cyclists on road sections and intersections and for a wide variety of accident typologies and risk factors. The analysis is conducted via a generalized ordered logit model due to its advantage in accommodating the ordered-response nature of severity while relaxing the proportional odds assumption.

The remainder of the paper is organized as follows. Section 2 describes the context and the data. Section 3 details the applied methodology. Section 4 presents the estimation results. Section 5 draws the conclusions and indicates directions for further research.

DATA

Cycling policies and safety in Denmark

Comprehending the safety of cyclists requires comprehending the context. In Denmark, half a million bicycles are sold annually to a population sporting a 90% bicycle ownership against a 44% car ownership. Danes use the bicycle for 17% of their trips and 24% of their trips under 5 km. Over one out of every three Danish adults cycles to work daily or once a week, and almost one out of every two Danish children bikes to school. On average, Danes cycle 1.4 km/day with a range going from 1.8-1.9 km/day for young adults to 0.6 km/day for elderly in their seventies (Cycling Embassy of Denmark, 2012). Although Danes cycle all year, seasonal effects make cycling vary from 1.7-2.0 km/day between April and September to 0.9-1.2 km/day between December and February (DTU Transport, 2012). Car ownership obviously limits cycling, but Danes in households with more than one car still bike 0.3-0.6 km/day (Danish Ministry of Transport and Energy, 2007). Probably this relates to the fact that the bicycle is chosen for both commuting trips (36% of trip-km for work purposes and 13% of trip-km for education purposes) and maintenance or discretionary trips (14% of trip-km for errands purposes and 37% of trip-km for leisure purposes).

Comprehending the safety of cyclists requires also understanding the historical perspective. Bicycles in Denmark have always been a dominant transport model, but the period between the 50's and the 70's witnessed a rapid growth in motorization rate and hence car traffic. The fuel shortage in the 70's and the increased public awareness of environmental and safety issues induced decision makers, urban planners and transport planners to shift toward walking and cycling. The shift implied heavy investments in infrastructure development. In fact, the national cycling network consists of 12,405 km of cycle lanes (17% of the national road network) under national (4,233 km), regional (5,873 km) and local (2,298 km) administration. The investments in infrastructure development are part of efforts in improving the safety of cyclists that led to the figure of 1.5 fatalities per 100 million km and the reduction of 70% of the fatalities over the last forty years (Pucher and Buehler, 2008).

Efforts in improving the safety of cyclists are made at the national level and the local level.

The Danish government promotes cycling and cycling safety through a national strategic plan comprising six initiatives: (i) maintenance of bicycle lanes (including illumination and road surface); (ii) construction of bicycle lanes and segregated bicycle road crossings along national roads; (iii) integration of bicycle infrastructure within new road construction projects; (iv) improvement of the safety of cyclists through the investigation of accident patterns; (v) enhancement of the integration between bicycles and public transport by providing convenient bicycle facilities and allocating space on-board for bicycles; (vi) encouragement of cycling initiatives by decision makers (Danish Ministry of Transport and Energy, 2007).

The Danish Road Directorate advocates cycling and cycling safety in its bicycle planning and infrastructure design concepts that include: (i) strategic planning of bicycle routes and cycling friendly urban environment for cyclists to enjoy a system of direct, short and fast paths; (ii) design of cycle paths and lanes for various capacities, including road signage, traffic management and solutions at intersections; (iii) definition of standards for bicycle parking spaces in residential areas, commercial areas, public institutions and public transport stations;

(iv) maintenance of cycle paths; (v) planning of bicycle route choice; (vi) promotion of utilitarian cycling, bicycle sharing and cycling tourism (Cycling Embassy of Denmark, 2012). Municipalities propose cycling strategic plans, the most recent being the plan for Copenhagen that aims at increasing bicycle mode share from 36% to 50% in 2025 while decreasing travel time by 15% and increasing safety perception in traffic to 90%. Initiatives include improving the bicycle route network by widening existing cycle paths and designing short cuts for bicycle routes, developing regional bicycle highways, reducing speed limit near education facilities, increasing bicycle parking facilities, introducing new bicycle sharing systems, and smoothly integrating cycling with public transport (City of Copenhagen, 2012).
In addition to strategic plans, educational campaigns are designed to encourage cycling and increase safety awareness among cyclists with major campaigns such as "Bike to work", "ABC – All kids bike" and "Light-on with Ludvig". The Road Safety Council promotes national campaigns aimed at increasing safety of cyclists through proficiency tests, light reflector use, careful behaviour at non-signalized intersections, blind spot awareness in right turns, and helmet use. Major cities such as Copenhagen, Fredriksberg, Odense, Aalborg, and Aarhus (Cycling Embassy of Denmark, 2012) promote local initiatives. For example, Odense promoted an initiative to increase road safety awareness by focusing on the identification by children and parents of safety concerns (Jensen, 2008).

Cycling accident dataset

Accident data were extracted from the accident database maintained by the Danish Road Directorate that is constructed on the basis of police records of accidents occurred on Danish roads and is composed of three files. The accident file reports details concerning accident type, weekday and time of day, level of severity, manner of collision, involved vehicles and road users, infrastructure characteristics, land use type, light and weather conditions. The person file provides information about each person involved in the accident, including demographics, alcohol or drug intoxication, seat belt or helmet use, license validity and injury severity. The vehicle file contains information about each vehicle involved such as make and model, maneuver prior to the accident, weight, registration date, and collision point.
Given the focus of the present study, only accidents involving cyclists and a third party in the five-year period 2005-2009 are considered. A five-year period is chosen since it provides an adequately large sample size, while it is short enough to control for changes in road and traffic conditions at the national level. Accidents involving a cyclist and a third party are chosen to overcome a dataset limitation that should be recognized. The Danish national accident database presents a limitation similar to other empirical accident databases because of the reliance on police crash reports and the possibility of under-reporting of cycling accidents, in particular for accidents without the involvement of a third party such as falls and collisions with fixed objects (see, e.g., Elvik and Mysen, 1999; Veisten et al., 2007; Aertsens et al., 2010). In Denmark, more than 10,000 cyclists are treated in emergency rooms as a result of an accident not involving a third party (Klarskov et al., 2005), while only 128 such accidents are reported in the Danish national accident database. Although caution should be taken in analysing cycling accident data due to under-reporting limitations (Wegman, 2012), police records remain the main data source for this type of analysis due to the richness of the collected data, in comparison with hospital records that often do not generally contain enough

background information on the bicycle accidents and are subject to recall and response bias among respondents (Kim et al., 2007). Hence, such data were previously used to explore cycling accident severity in the United States (Kim et al., 2007; Klop and Khattak 1999). Notably, the current study focuses solely on accidents involving a third party and hence is less susceptible to the aforementioned limitation.

The dataset for model estimation contains 8,892 complete records of accidents involving cyclists and other road users during the period between 2005 and 2009. Data report property damage only (57.2%), light cyclist injuries (17.3%), serious cyclist injuries (23.8%), and cyclist fatalities (1.7%). Damage only accidents include property damage and bruises. Light injuries require proper medical treatment, while serious injuries temporarily or permanently incapacitate (e.g., lesions, fractures, head trauma). Fatalities are defined as deaths within 30 days of the accident occurrence. The sample characteristics are described in Table 1. 95.2% of the accidents involved motorized vehicles, with most accidents (77.7%) involving passenger cars. Most accidents occurred in intersections (71.3%) and only 36.1% occurred where there was no cycle lane. The majority of the accidents occurred in areas where the speed limit is 50 km/h (74.8%), and half of the accidents (49.7%) happened while the cyclists were riding straight and the driver was turning. The accidents were distributed across seasons, although most of the accidents occurred on weekdays (87.3%), during daylight (80.8%) and on dry surfaces (74.8%). Only a small fraction of the drivers and cyclists involved in the accidents was intoxicated.

Table I – Sample characteristics

Variable	Categories	Percent	Categories	Percent
Cyclist injury severity	Damage only	57.2%	Incapacitating	23.8%
	Non-incapacitating	17.3%	Fatal injury	1.7%
Cyclist age (years)	9 years or less	1.8%		
	10-14	9.3%	40-49	15.0%
	15-19	11.4%	50-59	12.8%
	20-29	20.9%	60-69	8.6%
	30-39	13.4%	70 years or more	6.7%
Cyclist gender	Male	51.6%	Female	48.4%
Cyclist intoxication	No	97.9%	Yes	2.1%
Cyclist helmet use	No	44.6%	Yes	55.4%
Cyclist maneuver	Straight	88.7%	Left turn	7.8%
	Right turn	1.6%	Standing	1.8%
Cycling lane	Single	45.9%	Side of the road	12.5%
	Double	5.5%	No lane	36.1%
Other party involved	Pedestrian	2.0%	Car	77.7%
	Cyclist	2.7%	Van	6.5%
	Moped	4.8%	Heavy vehicles	3.4%
	Motorcycle	0.8%	Bus	2.1%
Other party maneuver	Driving straight	39.0%		
	Right turn	31.1%	Standing	4.7%
	Left turn	20.2%	Parking	0.6%
Other party vulnerable road	Male	7.1%	Female	3.3%

user (vru) gender				
Other party (vru) age	9 years or less	0.2%		
	10-14	0.4%	40-49	1.6%
	15-19	2.5%	50-59	1.3%
	20-29	1.5%	60-69	0.9%
	30-39	1.2%	70 years or more	0.8%
Other party (driver) gender	Male	61.6%	Female	28.0%
Other party (driver) age	15-19	4.7%		
	20-29	15.8%	50-59	13.5%
	30-39	18.4%	60-69	10.6%
	40-49	19.2%	70 years or more	7.4%
Other party intoxication	No	98.6%	Yes	1.4%
Accident location	Section	28.7%	Intersection	71.3%
Speed limit	Less than 50 km/h	3.6%		
	50 km/h	74.8%	70 km/h	4.4%
	60 km/h	9.3%	80 km/h or more	7.9%
Number of lanes	One	9.4%		
	Two	60.4%	Three or more	18.6%
Light conditions	Daylight	80.8%		
	Darkness	2.8%	Artificial light	16.3%
Visibility	Yes	95.4%	No	4.6%
Surface conditions	Dry	74.8%	Slippery	25.2%
Year	2007	21.0%		
	2008	21.4%	2010	16.7%
	2009	20.4%	2011	20.5%
Season	Spring	25.3%	Autumn	30.6%
	Summer	26.4%	Winter	17.7%
Day	Weekday	87.3%	Weekend	12.7%
Time of day	06:00-09:00	22.9%		
	09:00-15:00	34.8%	18:00-21:00	9.4%
	15:00-18:00	27.3%	21:00-06:00	5.5%
Land use	Residential (Sparse)	24.0%		
	Residential (dense)	34.5%	Industrial	10.0%
	Commercial	9.8%	Open areas	21.7%
Area	Copenhagen	31.6%	MidJutland	6.2%
	Sealand	21.8%	South Jutland	13.4%
	North Jutland	7.1%	Fyn	19.9%

METHODOLOGY

Given that the Danish database codes accident severity according to a four-point scale from the lowest to the highest level (0 = property damage only, 1 = light injury, 2 = severe injury, 3

= fatal injury), an ordered-response model of the injury sustained by cyclists seems the most suitable approach.

Given that the severity is an ordered-response discrete variable, an ordered logit model can be written in terms of probability of injury severity j for a cyclist involved in an accident (e.g., Long, 1997):

$$P\left(y_i > j\right) = \frac{\exp\left(X_i\beta' - \phi_j\right)}{1+\exp\left(X_i\beta' - \phi_j\right)} \qquad j = 1,2,...,M-1 \tag{1}$$

where X_i is a vector of explanatory variables, β is a vector of parameters to be estimated, Φ_j are cut-off points for the thresholds of the ordered model, and M is the number of categories of the ordered-response variables.

The ordered logit model bears the proportional odds assumption of equal relationship between each pair of severity categories. The generalized ordered logit model relaxes this assumption for all the explanatory variables in order to avoid incorrect, incomplete or misleading results. The probability of injury severity j for a cyclist involved in an accident is (e.g., Long, 1997):

$$P\left(y_i > j\right) = \frac{\exp\left(X_i\beta_j' - \phi_j\right)}{1+\exp\left(X_i\beta_j' - \phi_j\right)} \qquad j = 1,2,...,M-1 \tag{2}$$

where β_j is a vector of parameters that vary according to the cut-off points.

The proportional odds assumption may be violated by only a subset of variables, and hence the partial proportional odds model expresses the probability of injury severity j for a cyclist involved in an accident (e.g., Long, 1997):

$$P\left(y_i > j\right) = \frac{\exp\left(X_{1i}\beta_1' + X_{2i}\beta_{2j}' - \phi_j\right)}{1+\exp\left(X_{1i}\beta_1' + X_{2i}\beta_{2j}' - \phi_j\right)} \qquad j = 1,2,...,M-1 \tag{3}$$

where β_1 is a vector of parameters that does not violate the proportional odds assumption and is associated to a subset X_{1i} of explanatory variables, and β_{2j} is a vector of parameters that vary according to the cut-off points of the ordered logit model and is associated to a subset X_{2i} of explanatory variables.

The probability of injury severity j for a cyclist involved in an accident has a closed-form expression and the parameters are estimated through likelihood maximization:

$$LL = \sum_{n=1}^{N}\sum_{j=1}^{J} d_{nj} \ln P\left(y_i > j\right) \tag{4}$$

where LL is the log-likelihood function, N is the number of accidents, and d_{nj} is equal to 1 if the cyclist involved in accident n sustains an injury of category j and 0 otherwise.

Maximum likelihood allows estimating the parameters in vectors β_1, β_{2j} and Φ_j, and a Brant test prior to model estimation reveals which explanatory variables violate the proportional odds assumption (Long, 1997; Williams, 2006). The model has been recently implemented in the traffic safety literature for analysing injury severity in left-turn accidents (Wang and Abdel-Aty, 2008), investigating the effect of traffic congestion on the severity of road accidents (Quddus et al., 2010), and analysing bus accident severity (Kaplan and Prato, 2012). In this study, the partial proportional odds model is fitted with a user-written program in Stata (Williams, 2006). As the sign of model estimates does not always determine the direction of the effect of intermediate severity outcomes (Washington et al., 2003), the interpretation of the coefficients of intermediate categories requires elasticities to be calculated. As the classic elasticity measure cannot be calculated since the probabilities are not differentiable with respect to indicator variables (i.e., 0/1 variables), direct pseudo-elasticities are calculated as the percentage change in probability when an indicator variable is switched (i.e, from 0 to 1 or from 1 to 0) (Washington et al., 2003):

$$E_{x_{jnk}}^{P(y_i>j)} = \frac{P(y_i > j)[given\ x_{jnk} = 1] - P(y_i > j)[given\ x_{jnk} = 0]}{P(y_i > j)[given\ x_{jnk} = 0]} \tag{5}$$

where x_{jnk} is the k-th explanatory variable associated with injury severity j for a cyclist involved in accident n. Notably, the direct pseudo-elasticity is calculated for each injury severity j and each accident n, and hence the average direct pseudo-elasticity for each injury severity j is computed as the average over the entire sample of accidents (Kim et al., 2010).

The explanatory variables include the demographics of the cyclist and the third party involved, the behaviour of the cyclist, the behaviour of the third party, the infrastructure characteristics, and environmental conditions. In addition, year-specific dummy variables control for unobserved factors varying over the five-year period (e.g., time trend), and region-specific dummy variables control for unobserved factors varying across regions in Denmark (i.e., Copenhagen, Sealand, North Jutland, Mid-Jutland, South Jutland and Fyn).

RESULTS

Estimation of the generalized ordered logit model accounted for various combinations of the explanatory variables described in the data section, and for hypothesis testing for variable significance and category aggregation. Table 2 presents the best estimation results and table 3 shows the average pseudo-elasticities.

Prior to model estimation, a Brant test (1990) revealed that while the null hypothesis of equal coefficients across thresholds could not be rejected for some variables (e.g., number of lanes, land use), the estimated coefficients vary across severity thresholds for other variables (e.g., heavy vehicle involvement, road surface). Consequently, the generalized ordered logit model is preferred since not all the variables meet the proportional odds assumption.

Table II – Model estimation results

		Threshold between:		
Variable	Categories	0 and 1	1 and 2	2 and 3
Cyclist's age	less than 10 years old [b]	0.162	0.162	0.162
	10-14 years old [b]	-0.248**	-0.248**	-0.248**
	15-19 years old [b]	-0.265***	-0.265***	-0.265***
	20-29 years old [b]	-0.142*	-0.142*	-0.142*
	30-39 years old [a]	-	-	-
	40-49 years old [b]	0.262***	0.262***	0.262***
	50-59 years old [b]	0.513***	0.513***	0.513***
	60-69 years old	0.600***	0.639***	1.486***
	70 years old or more	0.709***	0.647***	2.344***
Cyclist's behaviour	Alcohol consumption - helmet use [b]	0.474*	0.474*	0.474*
	Alcohol consumption - no helmet use	0.630***	0.345	1.756***
	No alcohol consumption - helmet use [b]	-0.102**	-0.102**	-0.102**
	No alcohol consumption - no helmet use [a]	-	-	-

Cyclist's maneuver	Straight (cyclist) - straight (other party)	0.216***	0.234***	0.926***
	Straight (cyclist) - standing (other party) [b]	-0.346***	-0.346***	-0.346***
	Left turn (cyclist) - straight (other party)	0.513***	0.499***	1.486***
	Other conflict [a]	-	-	-
Cycling lane	Side of the road	0.033	-0.060	-0.563***
	No cycling lane [a]	-	-	-
Other party involved	Pedestrian	-0.308	0.103	-13.074
	Cyclist	-0.935***	-0.398*	0.060
	Moped [b]	-0.358**	-0.358**	-0.358**
	Motorcycle [b]	-0.352	-0.352	-0.352
	Car [a]	-	-	-
	Van [b]	0.234***	0.234***	0.234***
	Heavy vehicles	0.715***	0.950***	2.650***
	Bus [b]	0.216	0.216	0.216
Other party (vru)'s gender	Male [a]	-	-	-
	Female [b]	-0.734***	-0.734***	-0.734***
Other party (vru)'s age	less than 14 years old [b]	0.222	0.222	0.222
	15-19 years old [b]	0.485**	0.485**	0.485**
	20-29 years old [b]	0.563***	0.563***	0.563***
	30 years old or more [a]	-	-	-
Section type	Section [b]	0.125**	0.125**	0.125**
	Intersection [a]	-	-	-
Number of lanes	One lane [a]	-	-	-
	Two lanes [b]	0.149**	0.149**	0.149**
	Three lanes or more [b]	0.135*	0.135*	0.135*
Speed limit	less than 50 km/h [a]	-	-	-
	50 km/h [b]	0.221*	0.221*	0.221*
	60 km/h [b]	0.384***	0.384***	0.384***
	70 km/h	0.296*	0.426**	1.375***
	80 km/h or more	0.726***	0.693***	1.558***
Lighting conditions	Daylight [a]	-	-	-
	Dark or artificial illumination [b]	-0.131**	-0.131**	-0.131**
Surface conditions	Dry [a]	-	-	-
	Slippery (wet, snow, ice)	0.155***	0.003	0.427**
Land use	Residential (villas)	-	-	-
	Residential (apartments) [b]	-0.141***	-0.141***	-0.141***
	Commercial [b]	-0.209***	-0.209***	-0.209***
	Industrial	-	-	-
	Open areas [a]	-	-	-
Area-specific effect	Copenhagen	-	-	-
	Sealand [b]	-0.126*	-0.126*	-0.126*
	North Jutland [a]	0.060	-0.141*	-0.523**
	MidJutland	1.286***	0.458***	0.210
	South Jutland	0.613***	0.186*	0.069
	Fyn [b]	0.181**	0.181**	0.181**
Year-specific effects	2007 [a]	-	-	-
	2008 [b]	-0.048	-0.048	-0.048

2009 [b]	-0.225***	-0.225***	-0.225***
2010 [b]	-0.237***	-0.237***	-0.237***
2011 [b]	-0.162**	-0.162**	-0.162**
Constant	-0.959***	-1.615***	-5.962***
Number of observations			8892
Log-likelihood at estimates			-8321.47
McFadden rho-square			0.0740

Notes: [a] base category - [b] tested constraint for parallel lines
*** significant at the 0.01 level - ** significant at the 0.05 level – * significant at the 0.10 level

Table III – Average pseudo elasticities

Variable	Categories	Damage only	Light injury	Severe injury	Fatal injury
Cyclist's age	less than 10 years old	-6.54%	5.75%	13.04%	17.42%
	10-14 years old	9.67%	-9.97%	-18.15%	-22.42%
	15-19 years old	10.33%	-10.65%	-19.37%	-23.92%
	20-29 years old	5.61%	-5.52%	-10.74%	-13.58%
	30-39 years old [a]	-	-	-	-
	40-49 years old	-10.60%	9.17%	21.26%	28.62%
	50-59 years old	-20.98%	16.00%	43.69%	62.41%
	60-69 years old	-24.61%	12.40%	52.34%	296.59%
	70 years old or more	-29.14%	26.49%	44.63%	777.19%
Cyclist's behaviour	Alcohol consumption - helmet use	-19.48%	14.06%	41.17%	60.03%
	Alcohol consumption - no helmet use	-25.94%	51.28%	21.50%	457.36%
	No alcohol consumption - helmet use	4.09%	-3.86%	-7.95%	-10.25%
	No alcohol consumption - no helmet use [a]	-	-	-	-
Cyclist's vs. other party maneuver	Straight (cyclist) - straight (other party)	-8.69%	6.03%	16.97%	114.60%
	Straight (cyclist) - standing (other party)	13.27%	-14.23%	-24.49%	-29.65%
	Left turn (cyclist) - straight (other party)	-21.06%	17.17%	38.55%	304.23%
	Other conflict [a]	-	-	-	-
Cycling lane	Side of the road	-1.31%	10.30%	-3.63%	-61.35%
	No cycling lane [a]	-	-	-	-
Other party involved	Pedestrian	11.85%	-50.48%	10.72%	-130.52%
	Cyclist	32.31%	-74.88%	-28.33%	6.12%
	Moped	13.72%	-14.76%	-25.27%	-30.54%
	Motorcycle	13.44%	-14.58%	-24.67%	-29.67%
	Car [a]	-	-	-	-
	Van	-9.48%	8.12%	19.07%	25.79%
	Heavy vehicles	-29.40%	-13.34%	71.02%	1145.37%
	Bus	-8.78%	7.50%	17.67%	23.91%
Other party (vru)'s gender	Male [a]	-	-	-	-
	Female	26.43%	-31.39%	-46.37%	-53.20%
Other party (vru)'s age	less than 14 years old	-9.03%	7.66%	18.21%	24.72%
	15-19 years old	-19.92%	14.43%	42.05%	61.26%
	20-29 years old	-23.15%	15.70%	49.69%	74.38%
	30 years old or more [a]	-	-	-	-
Section type	Section	-5.03%	4.65%	9.84%	12.82%

	Intersection [a]	-	-	-	-
Number of lanes	One lane [a]	-	-	-	-
	Two lanes	-5.91%	5.68%	11.40%	14.59%
	Three lanes or more	-5.43%	4.95%	10.68%	14.03%
Speed limit	less than 50 km/h [a]	-	-	-	-
	50 km/h	-8.73%	8.67%	16.63%	20.93%
	60 km/h	-15.69%	12.56%	32.23%	44.97%
	70 km/h	-12.05%	-4.98%	32.27%	273.98%
	80 km/h or more	-29.81%	23.15%	57.40%	326.14%
Lighting conditions	Daylight [a]	-	-	-	-
	Dark or artificial illumination	5.18%	-5.09%	-9.91%	-12.53%
Surface conditions	Dry [a]	-	-	-	-
	Slippery (wet, snow, ice)	-6.23%	20.87%	-0.67%	47.62%
Land use	Residential (villas)	-	-	-	-
	Residential (apartments)	5.61%	-5.43%	-10.80%	-13.78%
	Commercial	8.16%	-8.31%	-15.40%	-19.15%
	Industrial	-	-	-	-
	Open areas [a]	-	-	-	-
Area-specific effects	Copenhagen	-	-	-	-
	Sealand	4.98%	-4.87%	-9.54%	-12.09%
	North Jutland [a]	-2.40%	21.57%	-10.08%	-45.08%
	Mid Jutland	-51.48%	125.25%	39.70%	22.95%
	South Jutland	-25.17%	66.42%	15.29%	7.11%
	Fyn	-7.30%	6.49%	14.49%	19.25%
Year-specific effects	2007 [a]	-	-	-	-
	2008	1.91%	-1.84%	-3.69%	-4.71%
	2009	8.84%	-8.87%	-16.77%	-21.01%
	2010	9.30%	-9.43%	-17.58%	-21.91%
	2011	6.40%	-6.33%	-12.22%	-15.41%

Cyclist's demographics and behaviour

Results show that cyclist injury severity is related to the cyclist's age, intoxication and helmet use, while it is not correlated to the cyclist's gender.

In comparison with accidents involving cyclists in their thirties, younger cyclists have a higher probability of lower injury severity, with the exception of young children under 10 years of age who are 13-17% more likely to suffer from severe and fatal injuries. Notably, the share of children under 10 years old in the total number of accidents is only 1.8%, much less than their 16% share in the total number of bicycle trips. The probability of cyclist injury severity increases with age over 40 years, with elderly cyclists being the most vulnerable group with a sharp increase in the probability of severe injuries and fatalities. In comparison with adult cyclists in their thirties, upon the occurrence of an accident the probability of fatal injuries increases by 297% for cyclists in their sixties and by 777% for cyclists in their seventies. Notably, the share of elderly cyclists over sixty in the total number of accidents is 15.7%, which doubles their 7.5% share in the total number of bicycle trips.

Results illustrate that alcohol involvement exacerbates and helmet use mitigates accident severity. Moreover, the current study presents trends similar to previous studies (Andersson and Bunketorp, 2002; Crocker et al., 2010, 2012) showing that helmet use rates among intoxicated cyclists are lower than among sober cyclists. In fact, the helmet use rate among intoxicated cyclists is 36.4%, while the helmet use rate among sober cyclists is 55.4%. In order to account for this correlation, cyclist intoxication and helmet use were combined into one variable with four categories: sober cyclists not wearing helmets (43.2%), sober cyclists wearing helmets (54.7%), intoxicated cyclists not wearing helmets (0.8%) and intoxicated cyclists wearing helmets (1.3%). Results suggest that helmet use is associated with 7-10% lower probability of severe cyclist injuries and fatalities for sober cyclists. Notably, effects are lower than the ones reported by studies focusing only on head injuries (see Elvik, 2011), but in the current study all injury types are considered. In comparison with sober cyclists who are involved in accidents while not wearing helmets, intoxicated cyclists are 60% more likely to die when wearing a helmet and 457% more likely to die when not wearing a helmet. Considering intoxicated cyclists with and without helmet, the probability of sustaining severe injuries are respectively 41% and 51% higher, and the probability of enduring light injuries are respectively 14% and 22% higher than the ones of sober cyclists involved in accidents while not wearing helmets.

Third party's characteristics and behaviour

Expectedly, the type of third party is correlated to cyclist injury severity. Relative to collisions between cyclists and cars, collisions between cyclists and mopeds or other cyclists have a lower probability of cyclist injuries or fatalities. Collisions between cyclists and motorcycles or pedestrians are not significantly different from accidents between cyclist and cars in terms of cyclist injury severity, possibly due to the scarcity of such collisions.

In the case that the other party is a vulnerable road user, gender and age are related to cyclist injury severity. When the vulnerable road user is a woman rather than a man, the probabilities of light, severe and fatal injuries decrease by 31%, 46% and 53%, respectively. Moreover, the same probabilities increase with the young age of the vulnerable road users, as to suggest that cyclist injury severity increases with the other party being young male vulnerable road users.

In the case that the other party is a vehicle, the most severe consequences are the result of accidents involving trucks, which comprise 3.4% of the accidents. Collisions between cyclists and trucks increase the probability of severe cyclist injury by 71% and the probability of cyclist fatality by 1145%. Collisions with vans and buses, comprising 8.5% of the accidents, bear also more severe consequences than collisions with cars and increase the probability of severe and fatal cyclist injuries by 17-26%. Interestingly, alcohol consumption by the driver of the third party involved is not significantly related to cyclist injuries, possibly due to the small number of registered cases of driver intoxication.

Movement conflicts between the cyclist and the third party

Cyclist injury severity is correlated with the traffic conflicts between cyclists and third parties. The vast majority of the accidents (88.7%) occurred while the cyclist was going straight. In

these accidents, the third party was going straight in 34.0%, turning right in 34.3%, turning left in 21.7% and standing or parking in the remaining 10% of the cases. Some accidents (6.8%) occurred while the cyclist was turning left and the other party was going straight.
The movement conflict related to the lowest probability of injuries and fatalities is naturally the case of a conflict between a cyclist going straight and another party standing. When comparing to cyclists going straight while the other party is turning right, the movement conflict with the harshest consequences is the conflict between a cyclist turning left and another party going straight, which increases the probability of severe and fatal cyclist injuries by 39% and 304%, respectively. The second harshest conflict occurs when both the cyclist and the other party are going straight, which increases the probability of severe and fatal cyclist injuries by 17% and 115%, respectively. All other maneuver conflicts do not entail significantly different probabilities of cyclist severity injury with respect to the base category.

Infrastructure characteristics

Cyclist injury severity, especially fatal injury, is significantly associated with infrastructure characteristics and in particular to higher speed limits and absence of cycling lanes.
Higher speed limits are related to a greater probability of higher cyclist injury severity. Relatively to speed limits lower than 50 km/h, speed limits of 50-60 km/h are associated with an increase of 17-32% of severe cyclist injuries and an increase of 21-45% of cyclist fatalities. The increase is far more pronounced for speed limits above 70 km/h, with 32-54% higher probability of severe cyclist injuries and 274-326% higher probability of cyclist fatalities.
The availability of cycling lanes is not significantly correlated with a decrease in minor or severe cyclist injuries, but it is strongly related (61%) to a decrease in the probability of cyclist fatalities.
Relatively to one-lane roads, road with two or more lanes are associated with a 10-15% increase in the probability of severe and fatal injuries. Accidents on road sections have a higher probability to result in higher cyclist injury severity levels, as the probability of severe and fatal cyclist injuries increases by 10-13% with respect to accidents on intersections.

Land-use

Accidents that occur in dense residential or commercial areas are associated with a slightly greater probability of lower cyclist injury severity with respect to areas with lower residential densities, industrial areas and open areas. In dense residential areas and commercial areas, the probability decreases by 5-8% for light cyclist injuries, 11-16% for severe cyclist injuries, and 14-19% for fatal cyclist injuries.

Environmental conditions

In comparison with dry road surfaces, slippery roads are mainly associated with a 21% increase in the probability of light cyclist injuries with respect to damage only accidents, and a 48% increase in the probability of cyclist fatalities with respect to severe cyclist injuries. Notably, a naturally high correlation exists between weather and surface condition

(Spearman's Rho = 0.825), and hence weather was not considered as explanatory variable to avoid problems of multi-collinearity.

In comparison with daylight, darkness is associated with a 10-13% lower probability of severe and fatal cyclist injuries. Notably, no significant difference was found between the effect of darkness and artificial illumination (t-test = 0.56) and these two categories were grouped. Time of day was only moderately correlated to light conditions (Spearman's Rho = 0.47), possibly due to differences in sunrise and sunset times across seasons, and the effect of time of day did not result significant in the model at the 0.10 level. Hence, light conditions appear the most prominent effect related to differences in cyclist injury severity across daily periods.

DISCUSSION AND CONCLUSIONS

The current study investigates the underlying risk factors of cyclist injury severity in accidents involving cyclists and a third party in Denmark. Model results provide insights regarding the effect of the various risk factors and stimulate thoughts about research directions and policy implications for enhancing the safety of cyclists.

Cyclist injury severity is related to the age of the cyclists, with children and elderly appearing the most vulnerable. Nevertheless, while the involvement rate of children in cycling accidents is much lower than their share in the total cycling trips, the involvement of elderly in their sixties and seventies is double their share in the total bicycle trips. Hence, cycling appears as a relatively safe transport mode for children, but as a more risky mode for elderly. Since in Denmark the cycling share among elderly over 60 years old is relatively high (see, e.g., Pucher and Buehler, 2008), and utilitarian cycling is associated with a reduced mortality risk (Andersen et al., 2000), policies should carefully approach the issue of safety of elderly cyclists. Namely, policies should on the one hand encourage people in the third age to cycle more and often, and on the other hand increase their awareness about safety.

Higher cyclist injury severity is correlated positively with the consumption of alcohol and negatively to the use of helmets. Alcohol consumption contributes to increasing injury severity in two important ways: (i) intoxicated cyclists wear helmets far less than sober cyclists, and (ii) intoxicated cyclists suffer more severe consequences because of alcohol consumption per se. It should be noted in fact that intoxicated cyclists wearing helmets while being involved in an accident have still a much higher probability to die (60%) than sober cyclists not wearing helmets while being involved in an accident. Possibly, helmet use mitigates injury severity effectively for intoxicated cyclists because of their diminished capability to mitigate themselves the consequences of the fall by controlling their movement and position. In Denmark, a law dating 1932 forbids drunken people to cycle while not being able to ride safely because of intoxication. Yet, the law is difficult to enforce and only a dozen fines are issued annually, while thousands of drunken cyclists enter emergency rooms (mainly for minor injuries) because of single-bicycle accidents with fixed objects (Klarskov et al., 2005). The current study shows that, although accidents involving drunken cyclists and a third party are rare, alcohol involvement dramatically increases the likelihood of death resulting from such accidents. Considering the amount of cyclists entering emergency rooms because of drink-and-ride behaviour, it appears beneficial reconsidering the law and its enforcement and proposing solutions to increase the report rate of accidents that would provide a more reliable picture of the drink-and-ride phenomenon.

Cyclist injury severity is related to maneuver conflicts between the cyclists and the other traffic. Results show that the harshest consequences for cyclists result from conflicts between a cyclist who is turning left and a third party going straight. Notably, the most prominent collision types in fatal accidents occur when (i) the two parties are going straight (48.3%), (ii) the cyclist is going straight and the third party is turning right (21.9%), and (iii) the cyclist is turning left while the third party is going straight (20.5%). However, the percentage of severe and fatal injuries is 29.4% upon the occurrence of a collision between a cyclist going straight and a third party going straight, 21.2% upon the occurrence of an accident between a cyclist going straight and a third party turning right, and 52.5% upon the occurrence of an impact between a cyclist turning left and a third party going straight. These findings add to previous results by the Danish Road Directorate illustrating that the most prominent conflicts in fatal accidents between the years 2003 and 2005 occurred when the cyclist and their collision partner were going straight, and when a cyclist was going straight and the collision partner was turning right (Danish Ministry of Transport and Energy, 2007). Likely, the current findings are related to the aforementioned public campaigns launched for increasing the awareness of drivers and cyclists to blind spots and right turns, and the general decrease in fatalities and serious injuries for cyclists involved in right turns over the last five years. Hence, further research is needed in order to identify in details the movements that lead to collisions between cyclists and other road users going straight, as well as the problems associated with cyclists turning left. Such research would help to design solutions involving self-evident, recognizable and forgiving road design (Wegman, 2012), and would help to launch educational campaigns targeted at further increasing road user awareness.

Conflicts relate also to the third party involved, since heavy vehicles, to a larger extent trucks and to a lesser extent buses and vans, are associated with higher cyclist injury severity. Notably, the "right-turn" campaign aiming at increasing the awareness of truck drivers and cyclists to the blind spots of trucks is associated with a reduction of the number of cyclist injuries (Cycling Embassy of Denmark, 2012). While accidents involving trucks and cyclists comprise only 3.4 % of the accidents, accidents involving buses and vans constitute an additional 8.6%, which raises a question regarding the necessary expansion of the campaign.

Higher speed limits of 70-80 km/h are associated with a dramatic increase in the probability of severe and fatal injuries. This result is important mainly in terms of cycling at the regional level, since the general speed limit in Denmark is 50 km/h within city limits and 80 km/h or more on motorways and outside urban areas (Cycling Embassy of Denmark, 2012). In Denmark, roads with a speed limit over 60 km/h are recommended to have shoulder curb lanes for traffic volumes up to 4,000 AADT, and cycle tracks with verges for higher traffic volumes (Cycling Embassy of Denmark, 2012). Indeed, current results show that cycle lane availability is an important factor in mitigating cyclist injury severity, as it is associated with a 60% decrease in the probability of cyclist fatalities. Hence, segregated cycle paths are a desired feature of regional cycling master-plans such as the regional bicycle super-highways in the Copenhagen area. Moreover, since information about traffic or cyclist volumes is not available in the current analysis, a possible further research direction could concern the effectiveness of shoulder curb lanes in traffic volumes up to 4,000 AADT, in conditions of both low and high cyclist traffic volumes.

The current study proposes an interesting dichotomy between accident occurrence and accident severity in terms of their location. In fact, while most (71%) of the analysed accidents occurred at intersections, their location on sections increases the probability of higher cyclist injury severity. Notably, the annual campaign "mind the side streets" launched by the Danish Road Safety Council is aimed at encouraging cyclists to be more vigilant in non-signalized intersections, and possibly additional educational campaigns could be launched to target safety issues also on road sections.

Slippery road surface is associated with an increase in the probability of cyclist injuries and fatalities, when compared to dry road surfaces. In Denmark, the "law on winter maintenance and cleaning of roads" takes care of slippery road and cycle path surfaces. The law defines three priority categories for maintenance of cycle paths: (i) segregated off-road cycle paths and cycle tracks along primary roads are cleaned every day around the clock; (ii) school routes and feeder paths are cleaned every day during daytime; (iii) minor paths are cleaned periodically. Moreover, the winter maintenance procedure prescribes cleaning, de-icing and repairmen of paths (Cycling Embassy of Denmark, 2012). It should be noted that the accidents on slippery road surface occur 36.9% of the times during winter, 35.4% during autumn, 12.9% during spring and 14.9% in the summer. Accordingly, the majority does not occur in winter as 63.1% occur in other seasons, possibly when cyclists are riding relatively fast during drizzles. Possibly, policies could be explored to improve the road surface porosity during other seasons, and educational campaigns could be designed to increase cyclist awareness about matching their driving style to weather and surface conditions.

Lower cyclist injury severity appears correlated to the occurrence of accidents during the evening. Although at first glance this finding may seem counterintuitive and in contrast to previous results (e.g., Kim et al., 2007), two factors may contribute. Firstly, the standards of the Danish road directorate for off-road cycle paths recommend sufficient illumination for the cyclists to ride at 25 km/h while easily distinguishing the path from the surrounding area (Cycling Embassy of Denmark, 2012). Secondly, the campaign "lights-on with Ludvig" most likely has increased the awareness of children and parents about the importance of cycling carefully in dark road sections and using lights and reflectors on the bicycles.

Accidents that occur in dense urban areas are associated with lower cyclist injury severity with respect to accidents that occur in sparse or open areas. Possibly, this result is related to the phenomenon of "safety in numbers". Namely, the number of cyclist injuries per capita decreases when cycling levels rise, as shown in an aggregate analysis of 47 cities in Denmark, 68 cities in California and 14 European countries (e.g., Jacobsen, 2003; Wegman, 2012). The current study suggests that the phenomenon of "safety in numbers" is related not only to injury rates, but also to injury severity, and that the effect on cyclist injury severity can be detected at the neighbourhood level because it depends on the local land use development.

While the current study is conducted in Denmark, results are possibly transferable to other countries, even with lower cycling rates. It is in fact striking that most results of the current study are in agreement with findings from North Carolina (Kim et al., 2007), despite the enormous differences in terms of cycling mode shares, utilitarian versus recreational cycling, infrastructure development, and educational campaigns launched to increase the awareness of drivers and cyclists to safety issues. The studies are in agreement with respect to the linkage between cycling injury severity and elderly cyclist age, cyclist intoxication, helmet use, high vehicle speed, involvement of heavy vehicles, and slippery road surface. Nevertheless, the current study adds information regarding the interaction between cyclist intoxication and helmet use, the effect of cycling paths, the effect of movement conflicts between cyclists and other road users, and the effect of the "safety in numbers" phenomenon.

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