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Published in:
Accident Analysis & Prevention

DOI (link to publication from Publisher):
10.1016/j.aap.2021.106353

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Accident Analysis and Prevention 161 (2021) 106353

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

Single-bicycle crashes: An in-depth analysis of self-reported crashes and estimation of attributable hospital cost

Anne Vingaard Olesen[a,*], Tanja Kidholm Osmann Madsen[a], Tove Hels[a], Mehdi Hosseinpour[b], Harry Spaabæk Lahrmann[a]

[a] The Traffic Research Group, Department of the Built Environment, Aalborg University, Thomas Manns Vej 23, 9220 Aalborg Ø, Denmark
[b] School of Engineering and Applied Sciences, Western Kentucky University, 1906 College Heights Blvd., Bowling Green, KY 42101, USA

ARTICLE INFO

Keywords:
Single-bicycle crashes
Attributable cost
Contributory factors
Cyclist cohort
Winter road maintenance

ABSTRACT

Cyclists' awareness of their risk of single-bicycle crashes is limited. Thus, knowledge of the most common contributory factors of single-bicycle crashes is required. Similarly, single-bicycle crashes and their costs to society are under-recognized by the public. The aim of this study was to conduct an analysis of single-bicycle crashes occurring in a cohort of cyclists in Denmark and supplement it with estimation of some attributable costs of single-bicycle crashes among all injured cyclists during one year treated in a hospital or emergency room in Denmark. We conducted a one-year follow-up of 6,793 active cyclists (mean age: 45.8 years) encountering 349 single-bicycle crashes (single-bicycle crash rate: 55 per 1,000 person-years). An in-depth analysis of the crashes suggested that daily winter road maintenance is crucial in colder climates and that the current cyclist infrastructure design gives rise to many single-bicycle crashes. Further analysis of the co-occurrence of the factors contributing to the crashes indicated that when the weather is warmer, the factors pertaining to the individual cyclist (and not the road authorities) dominate. The risk of sustaining a more severe injury (i.e. other than light bruises) once in a single-bicycle crash was 18 %. However, for cyclists above 50 years, this risk doubled compared with their younger counterparts, wholly due to a 4.7 times higher risk during the warm season. Among cyclists treated in hospital or emergency room, we estimated the attributable hospital cost of single-bicycle crashes at €1,701 and the attributable cost of municipality care at €417 in the first year after the injury (2019 prices). In cyclists aged 18–60 years and treated in hospital or emergency room, the estimated attributable risk of sickness benefit was 5.2 percentage points in the first year after the injury. We concluded that to increase cyclist safety, the road authorities should improve winter road maintenance and redesign cyclist infrastructure.

1. Introduction

Cycling is good for health and the environment (de Hartog et al., 2010; Holm et al., 2012). Studies suggest that while the switch from short car trips to bicycle trips has decreased the number of cyclist fatalities caused by car–bicycle crashes, the number of cyclist fatalities excluding motor vehicles have increased (Boufous and Olivier, 2016; Schepers and Heinen, 2013; Schepers et al., 2017b, 2017a), as has the number of serious cyclist injuries due to the rising number of single-bicycle crashes (Schepers and Heinen, 2013). Thus, preventive measures other than reducing the number of car–bicycle crashes are needed (Ohlin et al., 2019; Rizzi et al., 2020). Cyclists need to be more aware about the most common contributory factors of single-bicycle crashes (Hertach et al., 2018) because they underestimate the risk of severe injuries due to such crashes (Schepers et al., 2020).

Studies from Sweden and Switzerland have reported that removal of ice and snow is essential in winter (Hertach et al., 2018; Rizzi et al., 2020), whereas skidding due to gravel, dirt, and other substances causes single-bicycle crashes in all types of climates (Heesch et al., 2011). Road surface maintenance (involving potholes and surface deformation) is a preventive measure of common interest (Beck et al., 2019; Janstrup et al., 2018; Meuleners et al., 2020; Ohlin et al., 2019). Bad construction and design of bicycle paths, intersections, and on-road facilities present many problems (Fabriek et al., 2012; Ohlin et al., 2019; Vanparijs et al., 2016), with curbstones being a major contributory factor for single-bicycle crashes (Hertach et al., 2018; Niska, 2011). Objects, including road equipment such as bollards, railings, and posts, present problems at the roadside (Boele-Vos et al., 2017; Boufous et al., 2013; Meuleners

* Corresponding author.
E-mail address: avo@build.aau.dk (A.V. Olesen).

https://doi.org/10.1016/j.aap.2021.106353
Received 26 November 2020; Received in revised form 23 March 2021; Accepted 7 August 2021
Available online 18 August 2021

et al., 2020). Even a tree branch on the road can be hazardous (Heesch et al., 2011). Tram and railway tracks are also problematic (Beck et al., 2019; Hertach et al., 2018; Ling et al., 2017; Ohlin et al., 2019), as is roadwork close to bicycle infrastructure (Rizzi et al., 2020). A decrease in human errors as contributory crash factors relies on raising the awareness and conscience of cyclists. Studies have found that alcohol could be a significant contributory factor for single-bicycle crashes (Billot-Grasset et al., 2016; Dozza, 2017; Niska et al., 2013). The influence of distraction was assessed in a Dutch study (Davidse et al., 2014). Several studies have attributed crashes to evasive and dangerous maneuvers, such as sudden braking (Ekström and Linder, 2017; Hertach et al., 2018; Ohlin et al., 2019), especially when coupled with high speed (Boele-Vos et al., 2017; Ekström and Linder, 2017). Also, mechanical failures of the bicycle, such as chain problems, can result in a single-bicycle crash (Beck et al., 2019; Heesch et al., 2011). In some cases, more than one contributory factor triggers the crash, but evidence on the mutual interplay of co-contributory factors and the crash circumstances is scarce, and such investigations have not been conducted separately for single-bicycle crashes (Janstrup et al., 2018).

The majority (58–80 %) of cyclist injuries treated in the emergency room or hospital are due to single-bicycle crashes (Boele-Vos et al., 2017; Meuleners et al., 2020; Ohlin et al., 2019), implying that it is important to include these crashes in health economic evaluations (Schepers, 2012). Underreporting of single vehicle crashes is, however, a general problem, which counteracts the estimation of costs to society based on police crash data (Methorst et al., 2016). In Denmark, the proportion of single-bicycle crashes constituted 10 % of police-registered cyclist injuries in 2018, whereas the proportion of registered injuries in hospital data was 75 % (Statistics Denmark, 2020), suggesting underreporting in line with other countries, for example, the Netherlands (Boele-Vos et al., 2017; Schepers et al., 2017a).

Cycling is an often-used mode of transport in Denmark, with 14 % of all annual road trips being attributed to cyclists (National Danish Travel Survey, 2018). A large variation exists in the national bicycle share, and high bicycle shares are typical in large cities in particular. For instance, cyclists complete as much as approximately 28 % of all transport trips in Copenhagen (City of Copenhagen, 2019), which contrasts starkly with the negligible public recognition and knowledge of single-bicycle crashes in Denmark.

The aim of this study was to conduct an in-depth analysis of the contributory factors of single-bicycle crashes in a cohort of active daily-life cyclists in Denmark. The analysis included an evaluation of the co-occurrence of the various contributory factors. We also estimated some of the attributable costs to society (based on hospital data), which to our knowledge is new evidence on the health economic implications of single-bicycle crashes

2. Data and methods

We used data from two different sources for this study. Firstly, data from a follow-up study on a large cohort of active cyclists in Denmark self-reporting single-bicycle crashes. Secondly, through analysis of hospital data on all injuries sustained in single-bicycle crashes in Denmark during one year linked to other public registry data sources.

2.1. In-depth analysis of self-reported single-bicycle crashes

We obtained data for an in-depth analysis of single-bicycle crashes through follow-up of a cohort of 6,793 cyclists during one year from November 2012 through October 2013. The study involved 76,015 person-months of follow-up; 43,300 and 32,715 for males and females respectively; and 13,565, 31,869, 25,667, and 4,914 for the age groups 18–34, 35–49, 50–64, and 65 + years respectively. The participating cyclists received a web-based questionnaire on the first day of each month asking about the occurrence of any single-bicycle crashes during the previous month. In case of a positive response, the participants were asked for a prose description of their crash (among other details). Information on crash contributory factors was extracted from these descriptions through an in-depth reading. Per the literature, we had decided in advance which factors would be the focus of our in-depth analysis. If we received no reply, we excluded the cyclists from follow-up for that month. Most participants attended the study for 12 months (81 %). As per the inclusion criteria, the cyclists were required to be active, that is, make at least 3–4 trips per week in summer (May to August). At the time of recruitment, 84 % and 66 % reported that they cycled daily during summer and winter, respectively. For more details on the cohort, see Lahrmann et al. (2018).

We used Fisher's exact test for assessing the significance of an association between two categorical variables and Poisson regression for rate comparisons. In some cases, the p-values were accompanied by relative risk estimates. We performed all of the statistical analyses in the software package STATA 16 (StataCorp., 2019). Except for two calculations that were made by hand as explained in the next section. The significance level was 5 %.

An exposure weighted comparison of Poisson-distributed crash counts was calculated together with an age-standardized mortality rate. The relative bicycle traffic exposure in urban areas (traffic volume in 24 h – AADT) was as follows: winter: 0.75, spring: 1.06, summer: 1.09, autumn: 1.10 (Danish Road Directorate, 2020). As an example, provided that the crash counts of winter and spring are 168 and 49 respectively, the exposure adjusted ratio becomes $(168/0.75)/(49/1.06) = 4.9$ The age-standardized mortality rate was calculated through division of the number of observed deaths in the study population with the expected number of deaths assuming that the mortality in the study population was similar to that of the total Danish population. The age-standardization took place through estimation of the expected numbers of deaths (background population mortality rate multiplied by follow-up time in study population) in age strata and a final summation over all strata. Testing was performed in the Poisson distribution along the lines in the text book by Kirkwood and Sterne (2003).

Following Janstrup et al. (2018), we addressed the interplay among the various contributory factors through latent class analysis. A generalized structural equations modelling procedure in STATA 16 was used. To obtain convergence, we merged the contributory factors into main categories: daily operation, periodic maintenance, construction/design, roadwork, bicycle failures/conditions attributable to the cyclist/other, and curve. There are several advantages to latent class analysis over other standard clustering techniques, with the most important being that latent class analysis is a model-based clustering approach—a so-called "finite mixture model" that assumes that the data are generated by a mixture of underlying probability distributions. Being model-based implies that a statistical model is postulated for the population of single-bicycle crashes from which the sample originates. Parameter estimation takes place through proper maximization of a log-likelihood function, which means a less arbitrary choice of cluster criterion, such as in standard clustering approaches. Among other convenient features, latent class clustering does not vary depending on whether standardization of the variables has been made, and it handles different scale types (numerical, nominal, or combinations of both) (Vermunt and Magidson, 2002).

2.2. Estimation of attributable hospital cost, cost of care, and risk of sickness benefit

Our estimations of the attributable costs of hospital and municipality care and the attributable risk of sickness benefit within the first year after an injury due to a single-bicycle crash were conducted with a case-crossover design. We used each injured cyclist as his/her own control the year before the index treatment date at a hospital or in an emergency room. Devos et al. (2017) used this design. We conducted the statistical analysis of the cost data using generalized estimating equations with a gamma error distribution and log link. A modified Park test with coefficients just below 2 indicated that a gamma distribution was the most appropriate (Manning and Mullahy, 2001). We estimated the attributable costs as marginal effects. The estimation of the excess or absolute risk of sickness benefit was conducted using a binomial regression with an identity link function in the case-crossover design. The adjusted analyses controlled for gender, age (categories: 18–34, 35–49, 50–64, and 65+), and a dummy variable indicating whether the injured cyclist died in the year of the single-bicycle crash.

The data originated from three different sources: (1) hospitals and emergency rooms in Denmark, (2) home care data from Aalborg Municipality (home to approximately 220,000 citizens), and (3) data on recipients of sickness benefits between 18 and 60 years of age (an employer pays the benefits for the first four weeks after an injury). The hospital cost data were from 2014 to 2016, whereas the municipality and sickness benefit data were from 2015 to 2017. From the hospital cost data, we excluded pregnancy, birth, and maternity expenses, but included the costs of all other diagnoses as well as rehabilitation paid by the hospital authorities. Only those who were alive on arrival at the hospital were included in the register. For municipality data, we included all costs of home care, cleaning, nursing, and rehabilitation paid by the municipality. In Denmark, all citizens hold a unique social security number, which facilitates linkages of the different data sources, including hospital expenses as well as publicly paid care and sickness benefits.

3. Results

We conducted an in-depth analysis of the crash descriptions of 349 single-bicycle crashes self-reported by a cohort of 6,793 active cyclists during one year. The estimated rate of single-bicycle crashes was 55 per 1,000 person-years based on 6,335 person-years of follow-up. Next, we analyzed the population of all 9,623 emergency room-registered injured cyclists in single-bicycle crashes in 2015 in Denmark (injury rate: 1.7 per 1,000 person-years in the Danish population; approximately 5.7 million inhabitants).

3.1. Cohort of active cyclists self-reporting single-bicycle crashes

Table 1 shows the single-bicycle crash rates in the cyclist cohort. We found no gender differences in the single-bicycle crash rates ($p = 0.44$). The crash rate of the elderly (above 65 years) was lower than those of all other age groups, and no clear differences regarding age were observed in the cohort ($p = 0.10$).

Table 2 describes the implications and circumstances of the 349 single-bicycle crashes in the cyclist cohort. High proportions of the single crashes ended in relatively mild conditions (81 % with no or light bruises, 82 % not requiring medical treatment, and 87 % not requiring sick leave), but 65 suffered from more severe injuries than light bruises (10.3 per 1,000 person-years), mostly from fractures (40 % of all injuries) or joint distortion and ligament injuries (31 %). Once involved in a single-bicycle crash, the risk of sustaining a more severe injury (i.e., other than light bruises) was 18 %, whereas the risk of sustaining any injury, including light bruises, was 83 %. We detected a significant association between age and the risk of being more severely injured in a single crash for cyclists aged 50 and above; they showed twice as high a risk compared to their younger counterparts (<50 years), thus indicating a higher vulnerability in the older cyclists once they have been involved in a single-bicycle crash ($p = 0.002$; relative risk of 2.03). Among crash victims, 82 % used a helmet. Five percent of those who encountered a single-bicycle crash visited their general practitioner subsequently, whereas 15 % received treatment at a hospital or in an emergency room.

Table 1
Single-bicycle crash rates in cohort of 6,793 cyclists. Denmark (2012–2013).

Variable		Number of crashes	Follow-up in person-years	Crash rate per 1,000 person-years	P-value
Total		349	6334.6	55.1	
Gender	Male	206	3608.3	57.1	0.44
	Female	143	2726.3	52.5	
Age	18–34 years	67	1130.4	59.3	0.10
	35–49 years	128	2655.8	48.2	
	50–64 years	136	2138.9	63.6	
	65 + years	18	409.5	44.0	

Note: The p-values test the equality of crash rates

Table 2
Description of 349 self-reported single-bicycle crashes in Denmark (2012–2013).

Variable		N	%
Total		349	100.0
Gender	Male	206	59.0
	Female	143	41.0
Age (years)	18–34	67	19.2
	35–49	128	36.7
	50–64	136	39.0
	65+	18	5.2
Primary injury type	No injury	61	17.5
	Light bruises	223	63.9
	Joint distortion or ligament injury	20	5.7
	Pressed ribs	9	2.6
	Fracture (e.g., jaw, arm, hand, leg, and/or foot)	26	7.4
	Concussion	8	2.3
	Other head injury	2	0.6
Medical treatment	No	287	82.2
	Yes, at general practitioner	11	3.2
	Yes, both at general practitioner and emergency room/hospital	6	1.7
	Yes, at emergency room/hospital	45	12.9
Sick leave (days)	0	305	87.4
	1–3	22	6.3
	4–6	4	1.1
	7–14	5	1.4
	15–30	3	0.9
	Not known (including 30 +)*	10	2.9
Helmet use	Yes	286	82.0
	No	63	18.0
Road type	Intersection or roundabout	93	26.7
	Bicycle path or lane	150	43.0
	On road or other	106	30.4
Crash area	Urban	276	79.0
	Rural	73	21.0
Road surface	Dry	110	31.5
	Slippery	173	49.6
	Wet	66	18.9
Visibility	Fine	289	82.8
	Reduced	52	14.9
	Do not remember	8	2.3
Lighting	Day light	182	52.2
	Dark	105	30.1
	Dusk or dawn	62	17.8
Season**	Spring	49	14.0
	Summer	55	15.8
	Autumn	77	22.1
	Winter	168	48.1
Time of day	6 am–9 am	130	37.3
	9 am–3 pm	75	21.5
	3 pm–6 pm	78	22.4
	6 pm–11 pm	44	12.6
	11 pm–6 am	21	6.0
	Unknown	1	0.3

*The study participants self-reported crashes monthly, and thus, some long sick leave periods were truncated. ** Spring, summer, autumn, and winter range from March–May, June–August, September–November, and December–February, respectively.

Table 2 also displays information regarding the circumstances of the 349 single-bicycle crashes. Forty-three percent of the single-bicycle crashes occurred on a bicycle path, whereas 30 % and 27 % took place on a road and at an intersection or a roundabout, respectively. Seventy-nine percent of the crashes took place in an urban area. Regarding weather conditions, 68 % of the single-bicycle crashes occurred on a slippery surface caused by either snow/ice or water even when visibility was often good (83 %). When asked about the lighting conditions, the cyclists who had had a single crash responded that half of the crashes occurred in daylight, while the other half took place in the dark, or at dusk or dawn. Twenty-four percent of the single-bicycle crashes occurred on a dry surface, under good visibility conditions, and in daylight. Almost half of the crashes occurred in wintertime, with 3.4 times more single crashes than during spring ($p < 0.001$) and 4.9 times more crashes after controlling for the seasonal differences in the bicycle traffic volume ($p < 0.001$) (Danish Road Directorate, 2020). A similar comparison between winter and summer and between winter and autumn resulted in values indicating 3.1 and 4.5 times, and 2.2 and 3.2 times more crashes, respectively (all p-values < 0.001). We noticed a significant association between crash occurrence in winter due to slippery conditions brought about by water, snow, or ice ($p < 0.001$; 46 % of the total number of crashes took place in winter and a slippery or wet surface was involved). Table 2 shows that 37 % of the single crashes occurred in the morning rush hour, once again showing a clear association between crashing in the morning and slippery or wet conditions ($p < 0.001$; relative risk of 1.46 with single crashes in the morning due to ice/water accounting for 32 % of the total number of crashes). The morning rush hour between 6 am and 9 am comprised an average share of 28 % of the bicycle traffic volume during 24 h in urban areas in Denmark in 2013, whereas the afternoon rush hour between 3 pm and 6 pm comprised an average share of 27 % of the bicycle traffic volume (Danish Road Directorate, 2020). Nineteen percent of single crashes occurred in the evenings or nights, while the average share of the total bicycle traffic volume during these times was 14 % (Danish Road Directorate, 2020).

Table 3 presents the self-reported contributory factors of 349 single-bicycle crashes. A crash can have more than one contributory factor, and thus, the percentages sum up to more than 100 %. We divided the contributory factors across the main categories while referring to the role of the road authorities in relation to the contributory factors. In this study, factors related to the less than satisfactory daily removal of snow, ice, water, and other materials and objects played a role in 60 % of the single crashes, with snow and ice being the major contributor (48 %). Surface problems due to less than satisfactory periodic maintenance played a minor role (4 %) in the crash occurrences, whereas factors related to construction/design contributed to 25 % of the single-bicycle crashes, with curbstones being the major contributor (13 %). Bad visibility and roadwork markings played a role in 5 % of the crashes. Bicycle failures contributed to 6 % of the crashes, and included chain problems in particular (3 %). The self-reported influence of alcohol was relatively low (1 %). However, the aggregated proportion of self-reported conditions of the cyclists reached 18 %. The “other” category influenced 5 % of the single crashes.

Twenty-two percent of the single-bicycle crashes occurred along curves or when turning, and a strong association was observed between curves or when turning and snow and ice (88 % more crashes occurred due to snow and ice along a turn compared with the absence of a turn i.e. a relative risk of 1.88; $p < 0.001$). This finding was only observed for bicycle paths/lanes and at intersections/roundabouts.

3.2. Interplay of contributory factors

We estimated two latent classes because we hypothesized that the difference between the classes would be mainly attributable to the removal of snow and ice. Table 4 shows the estimated proportions of each factor influencing the occurrences of single-bicycle crashes for classes 1 and 2. In class 1 (64 % of all crashes), the contributory factors in the daily operation category played a role in 88 % of the single-bicycle crashes, which occurred from autumn through winter to early spring (when the weather in Denmark is typically cold, rainy, or marked by snow) and when the roads were slippery, either due to ice/snow or water. Most crashes occurred in the rush hour, and when daylight was limited and visibility was reduced. Co-contributory factors in this class involved construction/design. The proportion of the more severe injuries was lower than that in class 2. Daily operations played a marginal role in Class 2 (10 % of all crashes), and two dominant groups of contributory factors were observed for this class: construction/design

Table 3
Contributory factors of 349 self-reported single-bicycle crashes in Denmark (2012–2013).

Main group	Contributory factors	N	%
Daily operation		209	60.0
	Snow and ice	168	48.1
	Water	18	5.2
	Sand/dirt/gravel/leaves	17	4.9
	Object on road	10	2.9
Periodic maintenance		15	4.3
	Pothole	8	2.3
	Uneven surface	7	2.0
Construction/design		87	24.9
	Curbstone	45	12.9
	Object next to road (including road equipment)	14	4.0
	Bad or missing lighting	13	3.7
	Shoulder	13	3.7
	Low friction surface (including tracks and cobbles)	12	3.4
Roadwork	Roadwork	16	4.6
Bicycle failures		21	6.0
	Chain problems	12	3.4
Conditions of the cyclist		64	18.3
	Alcohol	5	1.4
	Speed	15	4.3
	Clothes, luggage, and shoes	15	4.3
	Maneuver failure	16	4.6
	Distraction	16	4.6
Curve	Curve or when turning	78	22.3
Other		18	5.2
	Animal	9	2.6
	Strong wind	6	1.7
	Sickness, sun, or unknown	3	0.9

Note: Cyclists may have added more than one contributory factor.

Table 4
Descriptions of two latent classes of single-bicycle crashes.

Factor	Proportion (%)	
	Class 1 (63.8 %)	Class 2 (36.2 %)
Daily operation	88.4	9.6
Periodic maintenance	3.7	5.3
Construction/design	21.0	31.8
Roadwork	2.3	8.7
Bicycle failures/conditions attributable to the cyclist/other	10.3	61.9
Curve or when turning	32.2	5.0
Gender male	59.1	58.9
Age below 50 years	58.9	50.5
Cycle path or lane	41.6	45.4
Urban area	76.7	83.3
Dark, dusk, or dawn	62.8	21.5
Reduced visibility	22.8	1.0
Slippery	96.6	18.9
October–April	95.1	36.5
Rush hour	68.2	44.4
More severe injury	16.3	22.7

and bicycle failure/conditions attributable to the cyclist/other, where the latter pooled group contained factors that the road authorities cannot (directly) influence. Most of these single crashes happened in daylight, summertime, and partly outside rush hours. Periodic maintenance played a minor role in both classes, whereas roadwork showed a higher impact on Class 2. Class 1 contained more young cyclists (<50 years old).

3.3. *Attributable costs of hospital and municipality care and attributable risk of sickness benefit*

Our study sourced hospital data, that is, injuries registered in emergency rooms/hospitals because of single-bicyclist crashes, from all of Denmark. Table 5 provides information on the gender and age distribution of the 9,623 hospital-registered injured cyclists in 2015 together with details about whether they died in the year of injury and at the primary injury site (as per the primary diagnosis assessments). More men were injured in the single-bicycle crashes ($p < 0.001$). One quarter of the injuries occurred among children and youth below the age of 18 years. Of those of the 9,623 injured cyclists who died in the year after the single-bicycle crash, half of the injuries were recorded for cyclists younger than 35 years, and the other half for those older than 35 years. However, the age-standardized mortality rate did not differ from that of the general population (age-standardized mortality rate of 0.82; $p = 0.18$). Regarding the primary injury site, almost half of the injured and 18 % had injuries on the upper and lower limbs, respectively, whereas 21 % suffered from a head or neck injury.

Table 6 shows the attributable hospital costs of single-bicycle crashes in Denmark. The costs amounted to €1,701 (95 % confidence interval (CI): €1,508–1,893) in 2019 prices, while the attributable cost of care totaled €417 (95 % CI: €0–834) in the first year after injury. We estimated the attributable cost of municipality care based on a much smaller sample comprising single crashes of citizens in Aalborg Municipality (implying wide confidence intervals). The estimation of the attributable absolute risk of receiving the sickness benefit from the government and home municipality was restricted to the sample of cyclists aged between 18 and 60 years and injured in single-bicycle crashes. We found a significant increased absolute risk of 5.23 % points (95 % CI: 4.35–6.11 % points) for receiving sickness benefits, which corresponds to a relative risk estimate of 1.63 (95 % CI: 1.51–1.76).

4. Discussion

The follow-up of our cyclist cohort showed that daily removal of ice and snow from bicycle infrastructure is crucial to reduce the number of single-bicycle crashes in countries such as Denmark in northern Europe, at least during relatively long and cold winters. When the weather is warmer, factors pertaining to the individual cyclists (and not the road authorities) play a major role, and the awareness and conscience of the individual cyclists become paramount to avoiding single-bicycle crashes. Bad infrastructure construction/design gives rise to many single-bicycle crashes, whatever the type of weather. In some cases when several contributory factors are at play, the responsibility of the crash can be shared between the road authorities and the cyclist him/herself; for instance, when a crash is attributed to both bad road conditions and high speed. In those mixed cases, the road authorities must seek to put their own house in order.

The risk of sustaining more severe injuries than light bruises was (marginally) higher in the "warmer season". Once involved in a single-bicycle crash, the risk of sustaining more severe injuries was twice as high in the older cyclists (aged above 50 years) than their younger counterparts; the former were subject to a higher risk (by 4.7 times i.e. relative risk of 4.7; $p < 0.001$) during periods without frost, indicating that the less robust Danish cyclists stay home when the weather is cold.

In addition, we estimated that single-bicycle crashes imply substantial public expenses associated with care, hospitalization, and sickness benefits. This is an important and novel result, because single-bicycle crashes are largely unconsidered in traffic safety planning by the Danish road authorities due to severe underreporting in the official road crash statistics.

4.1. *Two classes of single-bicycle crashes*

Although our work was based on only 349 crashes and 2 latent classes, we were able to detect the importance of ice and snow as the dominating contributory factor (together with construction/design) in one class of "cold season crashes". Infrastructure, human errors (conditions attributable to the cyclist, bicycle failures, and "others") and, to a certain extent, otherwise safe bicycle conditions characterized the other class of "warmer season crashes". Another Danish study by Janstrup et al. (2018) identified, through use of latent class analysis, 11 classes of cyclist crashes, wherein 4 classes exhibited especially high proportions of single crashes. A smaller class comprised a high share of crashes on slippery roads, but without separating single and multiparty crashes, this study could not identify a strong association between the occurrence of single-bicycle crashes and slippery surfaces. This may be attributable to cold weather data, which corresponded to mild winters. A recent report by Johansson and Bjørnskau (2020) categorized the safety of cyclists into two regimes based on the opinions of more than 2,500 cyclists. In summer, conditions such as potholes, uneven paving, and the presence of sand/gravel on the road were found to be the major problems, while in the winter the need for winter road maintenance was noted as the overall theme.

4.2. *Factors that can be influenced by the road authorities*

Skidding due to ice and snow was the main contributory factor in 21 % of the single-bicycle crashes leading to health loss (definition based on selection of severe diagnoses and/or long sickness absence) according to Ohlin and colleagues (2019). When skidding due to sand, gravel, leaves, and so on is added to 21 %, we obtain a cumulative estimate of 32 % (Ohlin et al., 2019), which is comparable with an appraisal of 31 % of single e-bike crashes in Switzerland (Hertach et al., 2018). Frost also played a role in the results of a Belgian study of 14–18 year old cyclists, but no explicit proportion was provided (Vanparijs et al., 2016). In our study, frost, snow, and ice influenced 48 % of the single-bicycle crashes. One explanation for the study is exposure, namely that our cohort members probably woke up early and rode their bicycles to work or school, and snow removal is typically unfinished then, because the preparation of the road facilities is prioritized for cars. In Sweden, studded winter tires and gravel are used more frequently to increase the surface friction, whereas in Denmark, we use salt and sand to remove the

Table 5
Descriptions of the 9,623 injuries in single-bicycle crashes registered in emergency rooms or hospitals in Denmark (2015).

Variable		N	%
Total		9,623	100.0
Gender	Male	5,337	55.5
	Female	4,286	44.5
Age (years)	0–17	2,374	24.7
	18–34	2,497	25.9
	35–49	1,712	17.8
	50–64	1,822	18.9
	65+	1,218	12.7
Died in year of injury	Yes	47	0.5
	No	9,576	99.5
Primary injury site	Head and neck	1,973	20.5
	Chest, stomach, lower back, spine, and pelvis	442	4.6
	Shoulder, arm, and hand	4,477	46.5
	Hip, leg, and foot	1,721	17.9
	Other	1,010	10.5

Table 6
Attributable costs of hospital and municipality care and attributable risk of sickness benefit in Denmark (2015–2016).

	N	Unadjusted	95 % CI	P-value	Adjusted	95 % CI	P-value
Attributable hospital cost	9,623	€1,637	€1,450–1,824	< 0.001	€1,701	€1,508–1,893	< 0.001
Attributable municipality cost of care	329	€192	€30–355	0.021	€417	€ 0–834	0.050
Attributable risk of sickness benefit	6,113	5.82 %	4.91–6.73 %	< 0.001	5.23 %	4.35–6.11 %	< 0.001

Note: The costs are in 2019 prices, whereas the (absolute) risk is in percentage points. "CI" denotes confidence interval. Adjustment was made for gender, age, and a dummy variable indicating whether the injured cyclist died in the year of the crash.

ice. Our finding stresses that cyclist safety, at least in Denmark, is highly dependent on proper winter maintenance. A recent Norwegian survey among cyclists corroborated that winter maintenance is important to ensure cyclists' safety during wintertime (Johansson and Bjørnskau, 2020).

Construction/design played a major role in our study (21 % in class 1 and 32 % in class 2), with curbstones (13 %) especially influencing the occurrence of many single-bicycle crashes, as in other studies (10 % in Ohlin et al. (2019), and 18 % (including other thresholds) in Hertach et al. (2018)). Objects placed along the road, such as road equipment, are also considered as a part of the infrastructure. Fabriek and colleagues (2012) conducted a survey among the visually impaired elderly and found that bollards, curbstones, and bicycle markings/shoulders are the most critical visual road infrastructure elements, and that it is advisable to paint curbstones white or use bright colors for road equipment (Fabriek et al., 2012; Schepers and den Brinker, 2011).

The role of periodic maintenance as means of crash prevention was found to be minor in this study (4–5 %). Ohlin et al.'s (2019) Swedish study showed that road surface problems were the main contributory factor for 9 % of single-bicycle crashes, whereas their impact was smaller in two other studies (Heesch et al., 2011; Hertach et al., 2018).

4.3. Elderly cyclists

The focus of the Dutch studies lies primarily on contributory factors of single-bicycle crashes in older cyclists, who face the highest risk of (severe) injuries and falls when (dis)mounting the bicycle or colliding with infrastructure such as curbstones (Boele-Vos et al., 2017). Research has indicated that impaired vision, problems with balance, stiffness, and loss of overview in complex situations are underlying factors for crashes among elderly cyclists (Davidse et al., 2014; de Hair et al., 2015; Dubbeldam et al., 2017; Fabriek et al., 2012; Kiewiet et al., 2017; Schepers et al., 2014; Twisk et al., 2017). Our study found that the rate of single-bicycle crashes equaled 55 per 1,000 person-years among active cyclists, but we could not decipher an age gradient. Our study population included a broad group of active cyclists of all ages; thus, older more susceptible cyclists, who do not cycle frequently, were not included. Our cohort was relatively young (average age: 45.8 years) and with relatively few crashes above the age of 65, which did not allow us to investigate further into hypotheses about this population. As mentioned earlier, the most vulnerable could have chosen to avoid cycling during wintertime. Our study did not specifically address problems of (dis) mounting the bicycle, and crashes during (dis)mounting were therefore not separated from crashes with other types of maneuver failures. However, only few of the crashes occurred during (dis)mounting.

4.4. More severe injuries sustained in single-bicycle crashes

A comparison of Tables 2 and 5 was not straightforward, but 10 of 65 injuries in the cyclist cohort (despite high helmet usage) were head injuries (15 %), which was only slightly lower than the proportion of head and neck injuries registered in the emergency rooms/hospitals (21 %; $p = 0.36$; notably, the data in the cohort were sparse). An Australian study by Boufous and colleagues (2013) on hospitalized cyclists injured in single-bicycle crashes found the proportion of head and neck injuries to be 30%, whereas 10, 43, 13, and 4 % showed injuries in the trunk area, on the upper limbs, on the lower limbs, and elsewhere, respectively. Half of the injuries were fractures. The proportions of injuries on the upper and lower limbs were similar between this study and the Australian one, but the fraction of head and neck injuries was higher in the latter perhaps because the cycling culture in Australia is different; most trips are dedicated to exercise and fewer to commuting, unlike Denmark. The results of a *meta*-analysis on the effect of wearing a helmet suggested that helmet use is especially recommended when there is increased risk of single-bicycle crashes, such as on slippery or icy roads (Høye, 2018).

4.5. Strengths and limitations of this study

Compared with other studies, we performed a prospective follow-up with monthly self-reporting questionnaires on single-bicycle crashes, which reduced the risk of recall bias and allowed some implicit control with regard to follow-up. However, we assessed that the self-reported exposure data were not valid because a cross tabulation of the self-reported number of km per week with information on the number of trips per week showed general inconsistencies. Nonetheless, we were able to derive a classification of single-bicycle crashes, which is meaningful in the light of the understanding of the contributory factors and their prioritization. This is because we conducted the analysis on individual crash descriptions with the possibility of choosing more than one contributory factor rather than confining ourselves to only one (main) factor. Another advantage of this study is its clear categorization of the contributory factors regarding the responsibility for prevention. Some of these clear-cut interpretations can probably be attributed to the use of the latent class analysis, which is superior to other standard clustering techniques (Vermunt and Magidson, 2002). Note that the estimated influence of the conditions attributable to the cyclist himself/herself can be too low, both due to self-reporting and because of an initial focus on maintenance and infrastructure, which may have influenced our analysis. Another drawback of this study and its relying on self-reports of contributory factors is the lack of an expert examination of the crash scene. In case of a cyclist riding off the road, an infrastructure specialist could have judged the bicycle path to be too narrow while the cyclist him/herself would contribute the crash, for example, to inattention because of lack of knowledge on infrastructure design. This limitation could imply some misclassification of contributory factors in particular factors that require some background knowledge such as on infrastructural design.

The registry-based study was complete and population-based, thereby utilizing the possibility of linking individual-level data from different public data sources and allowing us to estimate the attributable costs and excess risk of sickness benefits. Underreporting of traffic crashes in hospital data is an issue of discussion in Denmark (Laursen et al., 2005). We assume that the misclassification of traffic injuries takes place independently of their severity, thus leaving the cost estimates unbiased. One limitation of our registry study was the lack of information on the severity of the injuries in the emergency room/ hospital data in Denmark; thus, we were not able to analyze the expected gradient by severity.

4.6. Practical implications

To increase cyclist safety, road authorities could improve winter road maintenance and redesign cyclist infrastructure. Campaigns aimed at increasing public awareness of the risks and contributory factors of single-bicycle crashes would also be beneficial.

CRediT authorship contribution statement

Anne Vingaard Olesen: Conceptualization, Data curation, Formal analysis, Writing – original draft. **Tanja Kidholm Osmann Madsen:** Conceptualization, Data curation, Writing - review & editing. **Tove Hels:** Conceptualization, Writing - review & editing. **Mehdi Hosseinpour:** Conceptualization, Data curation, Writing - review & editing. **Harry Spaabæk Lahrmann:** Conceptualization, 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.

Acknowledgements

We thank two reviewers from the scientific committee of the International Cycling Safety Conference 2020 for constructive input to the manuscript.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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