Journal of Safety Research 87 (2023) 64–75

Contents lists available at ScienceDirect

Journal of Safety Research

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

Cyclist's travel distances and risk of falls in snowy and icy conditions in German cities

Martin Bärwolff *, Regine Gerike

Integrated Transport Planning and Traffic Engineering, Technische Universität Dresden, 01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 15 February 2023
Received in revised form 12 June 2023
Accepted 7 September 2023
Available online 15 September 2023

Keywords:
Winter Cycling
Distance Cycled
Cycling Safety
Single Bicycle Accidents
Survey Effects

ABSTRACT

Introduction: So far, no studies are known that estimate distance-based risks for cyclist falls in snowy/icy conditions compared to other conditions to account for differences in cycling levels in the different weather situations. *Method:* The number of cyclist falls was gathered from retrospective surveys in Germany. Cycling distances were obtained from the German Household Travel Survey "Mobility in cities – SrV," assigned to meteorological data, and validated against counts and own surveys. The number of falls per distance cycled and Risk Ratios for snowy/icy versus other weather conditions were estimated. *Results:* An average decrease of 53% in the distance travelled per person and day is estimated for snowy/icy days versus other days. This decrease is lower in regions with higher general cycling mode shares. We find average risks of falls from 9.5 to 16 (field surveys) up to 76.5 falls per 10,000 km (online survey) and average Risk Ratios for cycling in snowy/icy conditions of 20 (field survey conducted in times of other weather) to 36 (field survey conducted in times of snow/ice) and 38 (online survey conducted in times of snow/ice). The risk of suffering an injury in the event of a fall is lower in snowy/icy compared to other weather conditions. *Conclusions:* Seeing the current trend of growing general cycling levels in Germany, we expect more cycling in winter and, in case of unchanged winter weather and maintenance, a substantial increase of cyclist falls. The reduced risk of being injured in the event of a fall in snowy/icy conditions does not outweigh the higher risk of falling in the first place. *Practical Applications:* Improved winter maintenance on cycling facilities can help increase winter cycling and reduce the risk of falls at the same time.

1. Problem

Cycling as a means of active mobility comes with numerous benefits. It is environmentally friendly, inexpensive, flexible, space efficient and improves public health thanks to the physical activity related to active mobility (Gerike et al., 2021). Cycling is a suitable transport mode for most daily trips particularly in urban areas and can thus substantially contribute to mitigating the adverse effects caused by motorized private vehicles such as congestion, climate change, air pollution, noise, and land consumption. One challenge for promoting cycling is its sensitivity to weather. Thomas et al. (2013) report, based on the analysis of bicycle counts in the Netherlands, that 80% of daily fluctuation in cycling volumes can be explained by weather conditions. These findings are consistent with other studies in various regions and countries, based on count data (Zhao et al., 2018), travel surveys (Bergström & Magnusson, 2003; Hudde, 2023; Miranda-Moreno et al., 2013), and GPS traces of e-Bikes (de Kruijf et al., 2021). Temperature, precipitation, and wind are the main significant variables identified in these studies.

Snowy and icy conditions are of relevance for cyclist safety and the focus of this study. When people stop cycling in winter due to reduced comfort and safety concerns, this might lead to capacity problems for the alternative modes in wintertime and at the same time, people might get used to the alternative modes and resume cycling late in spring or not at all. When people continue cycling in snowy and icy conditions with a high fall risk, this causes suffering and social health cost.

Few studies on weather determinants of cycling activities have focused specifically on time periods with snow cover and icy conditions. Durth et al. (1993) counted bicycle traffic in German cities manually and found a decrease of 83 to 91% on snowy days compared to summer days. Zhao et al. (2018) found reductions of bicycle volumes of 75–85% on weekends with snow compared to weekends without precipitation at continuous automatic counting stations in Boston. Based on a longitudinal study in Vermont (U.S.), Flynn et al. (2012) found the likelihood of commuting by bicycle to

* Corresponding author.
E-mail addresses: martin.baerwolff@tu-dresden.de (M. Bärwolff), regine.gerike@tu-dresden.de (R. Gerike).

https://doi.org/10.1016/j.jsr.2023.09.005
0022-4375/© 2023 The Authors. Published by Elsevier Ltd.

decrease by about 10% with each inch of snow. Böcker and Thorsson (2014) analyzed panel diary data for Rotterdam (the Netherlands) using multivariate models and showed a reduction in the number of cycling trips per person and day by 28–38% and a reduction in the number of hours spent cycling per person and day by 28 to 41% on snowy days. Liu et al. (2015) found a reduction of the cycling mode share among non-commuters from 12% on days without snow-covered ground to 5% on days with snow in the Swedish National Travel Survey (NTS) data with substantial differences between the Northern and the Southern part of the country. Analyzing the use of a bicycle sharing system in New York (U.S.), An et al. (2019) observed a 79% reduction in trip numbers during snow periods, which is the main effect among all weather parameters.

These studies consistently showed substantial drops in cycling in snowy and icy conditions but also differences between regions, trip purposes, and distances. Böcker et al. (2019) found, based on their analysis of NTS data, significant reductions in cycling mode shares in Stockholm (Sweden) and Oslo (Norway) but not in Utrecht (the Netherlands), where the cycling mode share is significantly higher overall and varies less with different weather conditions. Hudde (2023) also analyzed NTS data and showed only a slight decrease of cycling in the winter months for the Netherlands but a substantial decline for Germany, which is twice as large as in the Netherlands. The decline was smaller for utilitarian cycling than for recreational cycling (Girod, 2005; Brandenburg et al., 2007; Griessbach, 2008; Schiller et al., 2011; Böcker et al., 2013; Thomas et al., 2013; An et al., 2019) and particularly longer trips were found to be avoided in winter (Bergström & Magnusson, 2003; Miranda-Moreno et al., 2013; de Kruijf et al., 2021).

All these studies have shown that cyclists adapt their travel behavior in winter and particularly in snowy and icy conditions. This may be due to discomfort caused by cold, precipitation or darkness, but cyclists may also be afraid of the increased risk of falling in these conditions. This high relevance of weather conditions for cycling levels and safety is contrasted by limited evidence on the actual risk for cyclists, specifically in snowy and icy weather conditions. Some studies have focused on the absolute risk of Single Bicycle Crashes (SBC) and thus excluded collisions with other road users (Eriksson et al., 2022). The data sources ranged from official national fatality statistics (Buehler & Pucher, 2017; Schepers et al., 2017; Feleke et al., 2018), police accident records (Yiannakoulias et al., 2012; Niska & Eriksson, 2013; Schepers et al., 2017; Fournier et al., 2019), and hospital data (Niska & Eriksson 2013) to weekly or monthly diaries (Hoffman et al., 2010; de Geus et al., 2012) and retrospective surveys (Aultman-Hall & Hall, 1998; Aultman-Hall & Kaltenecker, 1999).

In their retrospective surveys, Aultman-Hall and Hall (1998) and Aultman-Hall and Kaltenecker (1999) asked about accidents in the previous three years and the regular bicycle travel behavior of bicycle commuters. From that, Aultman-Hall and Hall (1998) calculated a risk of 9.5 cyclist falls per 10,000 km in Ottawa-Carleton, Canada, and Aultman-Hall and Kaltenecker (1999) calculated a risk of 12.9 cyclist falls per 10,000 km in Toronto, Canada. de Geus et al. (2012) derived an incidence rate of 1.5 slipping falls per 10,000 km from an online weekly travel diary on utilitarian cycling in Belgium. Eriksson et al. (2022) investigated SBCs from the Swedish STRADA database, which includes data from police records as well as from Accident & Emergency Departments. Using exposure data from the Swedish NTS, they calculated a risk of SBCs resulting in slight injuries (MAIS 1–2) of 3.9 (3.6–4.1) per 1,000 million kilometers traveled and of SBCs resulting in severe injuries (MAIS 3+) of 0.13 (0.11–0.15) per 1,000 million kilometers traveled.

No studies could be identified that quantified detailed risks of bicycle falls or SBCs per kilometer cycled for snowy and icy conditions but absolute risks without considering exposure are measured for specific weather conditions. This is mainly done for Scandinavian countries, often based on the Swedish STRADA database (Niska & Eriksson, 2013; Ohlin et al., 2019; Eriksson et al., 2022). Niska and Eriksson (2013) found about three times as many SBCs with serious injuries in summer months compared to winter months for the years 2007 to 2012. However, they did not account for exposure. And they also showed that in wintertime, most of the falls are caused by slipping on snow or ice. Slipping on ice or snow makes up almost three quarters of the SBCs in winter months. Niska and Eriksson (2013) showed that the majority of SBCs caused by slipping on snow or ice occurred in the morning hours between 6 a.m. and 10 a.m., which might result from late clearance of roads and cycling facilities. Ohlin et al. (2019) reported that in the period from January 2013 to April 2017, 14% of all bicycle crashes and 21% of all SBCs are caused by skidding on snow or ice. For the period of 2010–2019, Eriksson et al. (2022) found that about 13% of all SBCs occur on snow or ice, regardless of severity, and about the same percentage occur on grit left over from previous winter maintenance operations. Utriainen (2020) investigated insurance data on commuting incidents in Finland from 2016 to 2017 and found that around 30% of all SBCs happen on snow or ice, which is one of the most frequent characteristics. Olesen et al. (2021) analyzed a one-year monthly diary on cycling crashes and found that in 48% of all SBCs, snow or ice was reported to be a contributing factor.

Bärwolff et al. (2022) analyzed cyclist falls in different weather conditions based on retrospective survey data for German cities. In their study, 68% of cyclist falls in snowy or icy conditions were caused by snow or ice followed by own fault (10%), swerving obstacle/road user (7%) and step/curve (4%), the main proportion of cyclist falls in these weather conditions happened on untreated infrastructure facilities. One behavioral adaption of cyclists to deal with snowy or icy conditions on their facilities is to use the sidewalk. Bärwolff et al. (2022) showed that 81% of cyclists use the cycle path in dry conditions (19% the sidewalk) compared to 1% in snowy conditions (81% the sidewalk and 18% the carriageway); 75% of respondents rated winter services on cycle paths poor or fairly poor in their city (39% for sidewalks).

Based on observations and surveys, Bergström (2002) also described the problem that cyclists switch from the cycle path to the roadway if the winter road clearance service is insufficient, possibly creating new safety risks. If, on the other hand, bike lanes are cleared sooner than roadways, there is the risk that snow from the carriageway will be pushed back onto the bike lane or the sidewalk by winter maintenance. Therefore, bike lanes would have to be cleared at the same time or sooner (with appropriate care in subsequent clearing of the roadway) than the roadways. In addition, Bergström (2002) mentioned that applying excessive amounts of gritting materials can again lead to a decrease in skid resistance and a swift removal after the melting of snow and ice is important.

The studies mentioned above provide results on cycling levels in the different weather conditions, on cyclists' risk levels in winter (without considering exposure) and on the relevance of snowy and icy conditions for winter incidents. They indicate that risks per distance for cyclists are substantially higher in snowy and icy conditions compared to dry conditions. On the other hand, winter cycling volumes vary between countries and for different trip purposes, showing the potential for increasing cycling volumes throughout the year. Fast and reliable clearance of cycling facilities can reduce the risk of falling for those who cycle already and in addition, it may increase the levels of cycling in the winter and possibly also the other seasons.

No exposure-related risk measures have been quantified in previous studies, but they are needed to better understand the actual risk for cyclists, to demonstrate the relevance of the problem, and to support evidence-based cost-benefit assessments of winter maintenance strategies. This study addresses these gaps. It aims at quantifying the risk of single bicycle crashes in inclement weather conditions with a focus on "snowy/icy" conditions. The literature shows that cyclists are particularly affected by slippery snowy/icy road conditions; these might exist in clear, cloudy, or foggy weather, in situations with high or low humidity and with higher or lower wind speed. Variables from official weather data are purposefully combined to identify time periods with snow or ice on the roads and to allow for the comparison of those with all other time periods ("other weather"). We address the problems of under-reporting in official statistics particularly for single-bicycle accidents and for accidents with slight or no injuries by using multiple data sources for quantifying the risk of falls. This approach allows to estimate evidence-based risk ratios for snowy/icy versus other weather conditions and thus contributes to the scarce and fragmented literature that has generated relevant values on cycling levels and risks so far.

2. Method

2.1. Overview of the approach

Fig. 1 gives an overview of the research approach chosen for this study. Retrospective surveys were conducted online and in the field for quantifying numbers, severity, and underreporting of cyclist falls in snowy/icy as well as in other weather conditions. Cycling exposure was obtained from the recurring German Household Travel Survey (HTS) "Mobility in cities – SrV" (Ahrens et al., 2014) and validated against multiple data sources: field and online surveys from this study, manual counts and data from automatic bicycle counters in several German cities. Meteorological data were used to assign cycling exposure to snowy/icy and other weather conditions and to account for the substantial differences in the number of days for these two situations (German Weather Service DWD, Deutscher Wetterdienst, 2018). In the online and on-site surveys carried out as part of this study, the questions about falls and traffic behavior were asked separately for snowy/icy and other weather conditions. Based on the data on falls and exposure in snowy/icy and other weather conditions, the risk assessment was completed using the equations shown in Fig. 1. Further details on the data used in this study are provided in Bärwolff et al. (2022).

In this study, risk was defined as the number of falls per distance cycled. The risk in snowy/icy conditions, for example, was calculated by dividing (1) the mean number of falls in snowy/icy conditions per person during the study period (known field and online surveys carried out as part of this study) by (2) the mean distance cycled in snowy/icy conditions per person (known from the HTS) and (3) the number of days with snow/ice in the study period (known from the German Weather Service DWD, Deutscher Wetterdienst, 2018). Subgroups for weather conditions, gender, and age were formed consistently both for the number of falls from the surveys and for the distance cycled from the HTS. The Risk Ratio (RR) of falling in snowy/icy conditions compared to other weather conditions was calculated by dividing the numbers of falls per distance traveled in snowy/icy conditions by the number of falls per distance traveled in other conditions. Confidence Intervals (CI, 95%) were calculated for mean values of cyclist falls and distances traveled by bicycle. As these two variables originate from different samples, Fieller's theorem (Fieller, 1940) was applied for approximate error propagation of their ratio. CI were not calculated for the proportion of days with snow/ice, as this variable includes all days of the five-year period for which cyclist falls were surveyed.

2.2. Self-reported falls from retrospective surveys

Retrospective field surveys among cyclists were conducted in 17 areas in the cities of Aachen, Altenberg, Dresden, Münster, Roetgen and Simmerath. These cities are within a 100 km radius of the locations of the involved research teams and include both large cities of lower altitude and smaller cities of higher altitude in western and eastern Germany. The surveys were conducted on sidewalks and cycle paths on major roads, sidewalks on access roads, crossing facilities and public transport stops on working days excluding school breaks and bank holidays in both snowy/icy and other weather conditions (parallel to the video recordings for the manual counts). All persons aged over 14 years were included in the survey. Cyclists were not approached while cycling, but only when pushing the bicycle, during waiting times or at bicycle parking facilities.

In addition, an online survey with for the most part identical content was conducted in the period from mid-January to early February 2017. Respondents for this survey were recruited via various internal and external channels of the TU Dresden and the Fed-

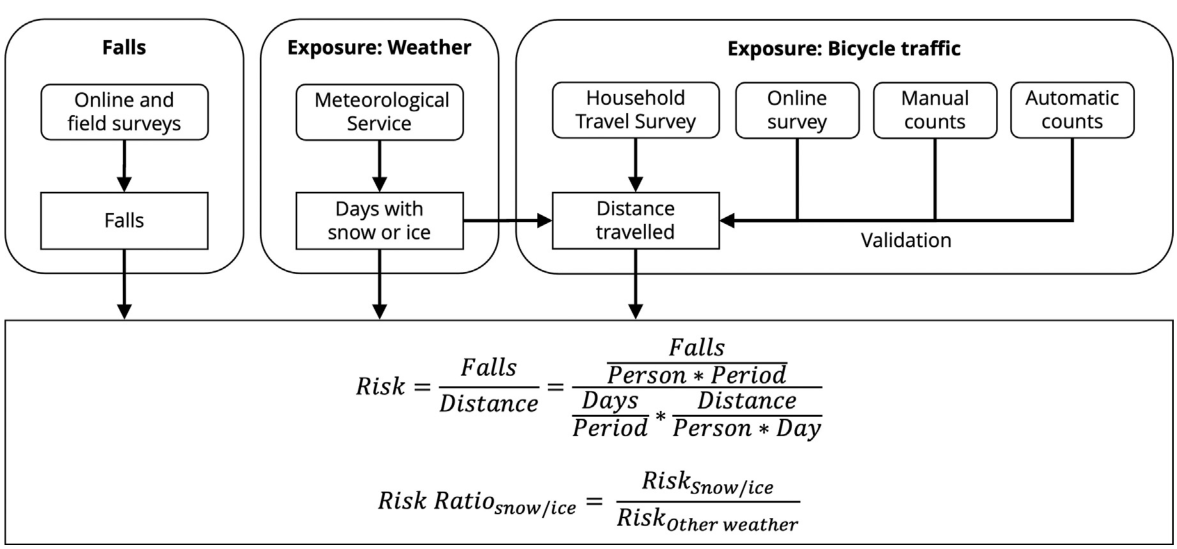

Fig. 1. Overview of the research approach used, the data sources used and the calculation formulas for cyclist if cycled per distance and Risk Ratio (RR).

eral Highway Research Institute (BASt). The link to the online survey was first distributed to around 8,000 employees and 2,000 student assistants of TU Dresden on 10 January 2017. On 30 January 2017 the link was also published via TU Dresden's Twitter account with (at that time) more than 7,000 subscribers and on 2 February 2017 via a call in the TU Dresden's student newsletter. On 1 February 2017, the link to the online survey was distributed among the (at that time) approximately 400 employees of the Federal Highway Research Institute and published on the department's intranet.

The respondents of both surveys were asked about the number of self-experienced cyclist falls on public roads, paths, and sidewalks in the 5-year period before the survey in both snowy/icy and other conditions. Among the 2,104 persons interviewed in the field, 2,090 could remember the number of falls as cyclists in this period. They reported a total of 600 cyclist falls. Among the 3,338 online respondents, 3,208 people could remember the number of falls as cyclists in this period. They reported a total of 5,110 cyclist falls. In total 5,298 participants reported 5,710 cyclist falls.

In addition to the question about the total number of falls, all respondents were also asked about the kind of medical treatment they received after their most recent falls in both snowy/icy and other weather conditions (none, doctor's visit, hospitalization of less or more than 24 hours). Respondents in the online survey were also asked whether the fall was reported to official databases (police, insurers). Since several respondents did not remember any falls from a five-year period, the sample size for detailed information about the respective last fall is reduced compared to this question. In the field surveys, 184 respondents gave such information on their last cyclist fall in snowy/icy conditions and 176 respondents gave information on their last cyclist fall in other conditions. On the other hand, 989 online respondents gave such information on their last cyclist fall in snowy/icy conditions and 884 online respondents gave information on their last cyclist fall in other conditions.

2.3. Weather data

Weather data were obtained from the official German Weather Service DWD (Deutscher Wetterdienst, 2018). For respondents in field surveys and for bicycle counts, data were linked to the weather station nearest to the location of the survey or count. For respondents in online surveys and HTS, the nearest weather station to their place of residence was used. The scheme for assigning each day of the investigated time periods to either the category "snowy/icy weather" or "other weather" is shown in Fig. 2. The following data were obtained from DWD for each day of the study periods:

- daily minimum temperature
- height of snow and height of freshly fallen snow at 7 a.m.
- daily precipitation as the total from 6 a.m. on the reference day to 6 a.m. on the following day

Days were defined as "snow/icy" when either previously fallen snow had not yet thawed, new snow had fallen and/or liquid precipitation fell during days with minimum temperatures close to the freezing point.

The analysis of weather data shows a substantial variation in the number of days with snowy/icy conditions. For example, the proportion of days classified as "snowy/icy" ranges between 13% (Munich) and 6% (Cologne) for the weather data from 2010 to 2016. Inter-annual variations within a city are even greater than geographical differences between cities. For example, the proportion of showy/icy days in the city of Dresden dropped from 27% in 2010 to 8% in 2011. This demonstrates the high relevance of this variable for risk assessment, it should be considered as detailed as possible.

2.4. Cyclist volumes

The changes in cyclist volumes on snowy/icy days were quantified based on the following data sources:

- raw data from 22,772 respondents in the German HTS „Mobility in Cities – SrV" (Ahrens et al., 2014),
- daily traffic volumes from 43 automatic bicycle counters from nine German cities,
- short term cyclist counts from video recordings from this study at 14 sites on both snowy/icy days and other days, and
- information on usual travel behavior on both snowy/icy days and other days provided by 3,333 of the participants in the online survey carried out as part of this study.

2.4.1. Household travel surveys (HTS)

Data from the HTS "Mobility in Cities – SrV" from 2013 (Ahrens et al., 2014) was analyzed in terms of mode choice in different weather conditions. This HTS collects cross-sectional data in individual survey waves that are run every five years. Representative samples are not taken for Germany but for specific cities and regions. In the 2013 wave used for this study, HTS with identical sampling and survey methods were conducted in more than 50 cities and regions spread all over Germany. Respondents reported

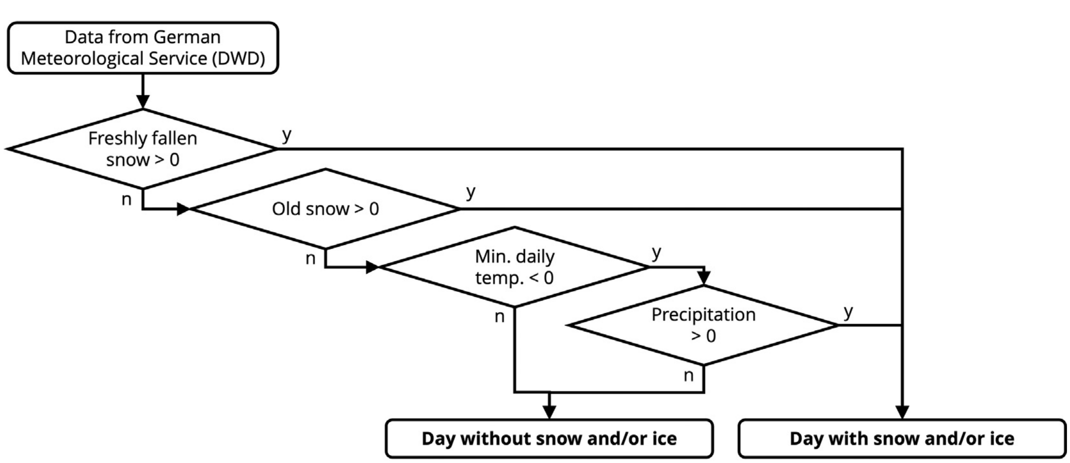

Fig. 2. Scheme to assign a day to have snowy/icy or other weather conditions using meteorological data.

their trips and further information on person and household characteristics for one diary day including only working days, school and bank holidays were excluded. For this study, a pooled sample from the HTS "Mobility in Cities – SrV" was used including data from a fixed set of cities that represent the German cities well, this is the so-called Städtepegel (Ahrens et al., 2015). Using the HTS data, we summed the distances per trip on the reporting day for each respondent. Depending on whether the reporting day was a day with snowy/icy conditions, the mean distance cycled per person and day for both snowy/icy and for other weather conditions was calculated on this basis. These data were also used as denominator for calculating risk factors and risk ratios (RR).

2.4.2. Online survey

The online survey included questions about respondents' travel behavior in snowy/icy and other weather conditions. The questionnaire did not contain a trip diary for a specific reporting day but instead questions on the frequency of use for the motorized modes (car and motorized two-wheelers), public transport, cycling and walking. The following five pre-defined categories were used to ask for bicycling in typical summer weather conditions which are pleasant in Germany: almost daily, 1–3 days per week, 1–3 days per month, less than once a month, never. Similar categories are also used in the German NTS and in the HTS "Mobility in Cities – SrV" (Ahrens et al., 2014). The five categories were translated into a specific number of days for quantifying bicycle use. For example, the category "almost daily" means four to seven days per week and was translated into 5.5 days per week. Questions on mode change in snowy/icy weather conditions included the following pre-defined categories that compare the previously specified frequency of bicycle use in typical summer weather with snowy/icy conditions: "more frequent," "as always," "less frequent," and "never." If the category "as always" was chosen by a respondent, the same frequency class as for other weather than snow/ice was assigned. If the categories "more frequent" and "less frequent" were chosen, the next higher or lower frequency class was assigned. The calculated annual days of use for each transport mode were averaged over all respondents and compared between snowy/icy and typical summer weather conditions.

In addition, we asked those respondents who reported a lower frequency of trips for snowy/icy conditions than for other conditions about the reasons for this change in behavior.

2.4.3. Manual counts

Video recordings were carried out parallel to the field surveys. Video cameras were installed along 14 street sections within the seven study areas observing sidewalks and cycle paths. Video data for all study sites were collected for snowy/icy and other weather conditions in the years 2015–2018. This long period was necessary to ensure snowy/icy weather conditions at all study sites. Data were collected on working days excluding school breaks and bank holidays. Similar weekdays and time periods were chosen for snowy/icy and the other weather conditions to ensure comparability. At each location, cyclists on sidewalks or cycle paths were counted from the video for 45 minutes. At places with low bicycle traffic, up to 315 minutes were counted to generate a meaningful sample. Further videos were recorded at different sections, but these are not included because less than 50 cyclists were counted in six hours of video on days with other weather conditions than snowy/icy. In total 3,101 cyclists were counted in the 14 sections.

2.4.4. Automatic counts

Data from 44 automatic permanent bicycle counters in nine German cities were processed. These cities were chosen because they are located in different parts of Germany and because count data were either freely accessible online or provided by the local administrations. All bicycle counters are placed on dedicated cycling facilities (visually marked cycle lanes or physically separated cycle tracks). The data came from different time periods for the different cities and counters. For example, the counter data in Cologne start at the beginning of 2010 and, depending on the counter, extends to the end of 2014 or the end of 2016. In contrast, the period of data for all counters in the cities of Berlin and Rostock ranges from the beginning of 2016 to the end of February 2017. Periods of sensor failure were excluded resulting in a dataset with over 50 million counted cyclists on almost 45,000 days. The average change in cyclist volumes on snowy/icy days versus other days on a city level was calculated as the mean of the changes of all counters in a city.

3. Results

3.1. Distances traveled by bicycle

3.1.1. Household travel surveys (HTS)

Fig. 3 gives an overview of cycling distances in HTS by age, gender, and weather conditions. This distance is about 1.5 km per person and day in the whole sample and about 1.6 km (95% CI [1.5, 1.7]) on reporting days with weather conditions other than snowy/icy. It decreases to about 0.8 km (95% CI [0.8, 1.0]) per person on reporting days with snowy/icy conditions, which is a statistically significant decrease of 53% (95% CI [45%, 51%]).

Female HTS respondents cycle an average distance of 1.4 km (95% CI [1.3, 1.5]) on reporting days with other weather conditions and an average distance of 0.6 km (95% CI [0.5, 0.7]) on reporting days with snowy/icy conditions. Male HTS respondents on the other hand cycle an average distance of 1.9 km (95% CI [1.8, 2.0]) on reporting days with other weather conditions and an average distance of 0.9 km (95% CI [0.7, 1.1]) on reporting days with snowy/icy conditions. The decrease on reporting days with snowy/icy conditions compared to reporting days with other weather conditions is statistically significant for both genders.

For reporting days with other weather conditions, the average daily cycling distances differ statistically significantly between all age groups. The mean daily distance covered on reporting days with other weather conditions is highest among persons aged 18 to 44 with 2.5 km (95% CI [2.3, 2.7]) and lowest among persons aged 65 and older with 0.7 km (95% CI [0.6, 0.8]). Likewise, on snowy/icy reporting days, persons aged 18 –44 cover the longest cycling distance (1.4 with 95% CI [1.1, 1.7]) and persons aged 65 and older cover the shortest cycling distance (0.2 with 95% CI [0.1, 0.3]). The difference between persons aged 18 to 44 and those aged 45 to 64, who cycle an average of 1 km (95% CI [0.7, 1.3]) per snowy/icy day, is not statistically significant.

Due to the smaller sample sizes of snowy/icy reporting days (around 15% of all trips), no significant difference between genders or age groups can be identified in the magnitude of the decrease of average daily cycling distances on snowy/icy reporting days versus reporting days with other weather conditions. However, respondents aged 65 years or older report the highest average decrease of 70% (95% CI [55%, 85%]).

3.1.2. Validation with multiple data sources

The analysis of the online survey shows, that 55% of those respondents who use the bicycle (almost) daily in other weather conditions state that they use the bicycle less often during snowy/icy conditions (of which 12% never use it during snowy/icy conditions). In contrast, among those respondents who use the bicycle in other weather less frequently than daily, 87% state that they use the bicycle even less frequently during snowy/icy conditions (of which 48% never use it during snowy/icy condi-

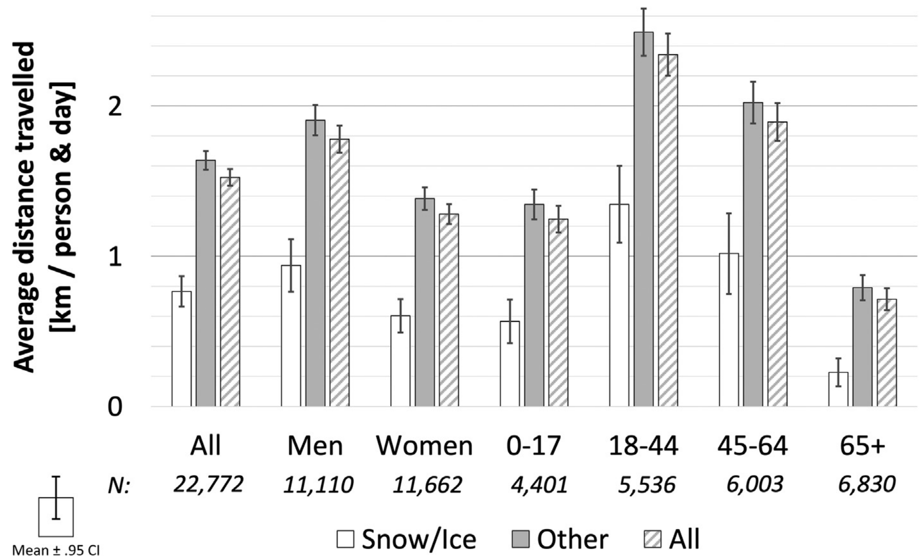

Fig. 3. Average daily cycling distances covered by HTS respondents in various weather conditions, by gender and age.

tions). After translating this categorical information into average numbers of days with bicycle use per person and month, the mean decrease in days of bicycle use across all online respondents is 59% during snowy/icy conditions compared to other weather conditions. Changes in bicycle use reported to the online survey are shown in Fig. 4.

Among those respondents who stated that they cycle less in snowy/icy conditions, 87% stated an increased risk of falling as the reason, and 74% stated poor winter maintenance on cycling facilities as the reason. In contrast to that, less than half of the respondents (46%) stated comfort losses as a reason (Fig. 5). Also, compared to the risk of falling, the risk of colliding with other road users was mentioned by fewer respondents (43%).

The manual video-based counts show a decrease of 54 to 85% in the four sections in the city of Aachen and a decrease of 56 to 88% in the eight sections in the city of Dresden in snowy/icy conditions compared to other weather conditions. In contrast, the decrease in cycling in snowy/icy conditions on two sections in the city of Münster (which has one of the highest cycling shares among German cities) is 13% and 21%, respectively. Across all sections, the average decrease in bicycle traffic is 63% (95% CI [51%, 75%]). Overall, the decrease in snowy/icy conditions is significantly greater among female cyclists than male cyclists. Regarding different age

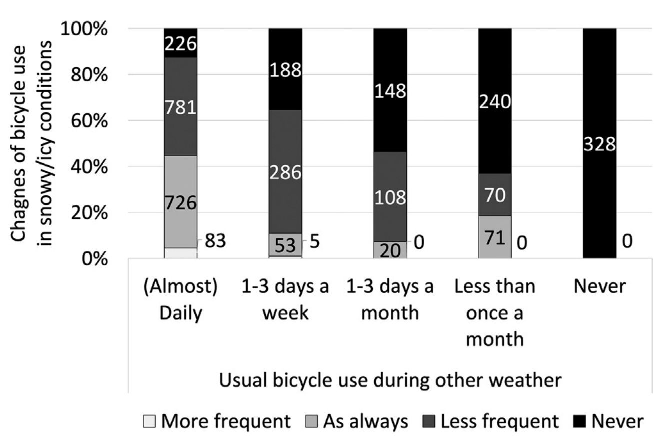

Fig. 4. Modification of bicycle use in snowy/icy conditions compared to usual use reported by online respondents.

groups, there are no significant differences. The results of the manual counts are shown in Table 1.

Data from the 44 automatic counting stations in the nine cities included in this study as presented in Fig. 6 show a mean decrease of 53% (95% CI [48%, 58%]) in daily cyclist volumes in snowy/icy conditions. The strongest decrease with 67% (95% CI [58%, 76%]) was identified at the stations in Dresden. The decrease in Münster is lowest with 9%, followed by the station in Freiburg with 29%.

3.2. Risk of falling with a bicycle

On average, all respondents in our field studies reported 57 cyclist falls per 1,000 person-years regardless of weather conditions. A similar rate of 55 falls per 1,000 person-years was found by Olesen et al. (2021) for single bicycle crashes among active cyclists in a one-year follow-up study in Denmark. In contrast, participants in our supplementary online survey, which also took place during a period of snow and ice, reported an average of 319 falls per 1,000 person-years.

Taking exposure into account (traffic volume and temporal proportion of weather conditions), an overall average of 0.9 falls per 10,000 km cycled (95% CI [0.7, 1.1]) are reported in field surveys that were conducted during times of other weather (see Fig. 2). This is less than during the field surveys conducted in other weather conditions, but the difference is not statistically significant (1.2 falls per 10,000 km cycled with 95% CI [0.9, 1.5]). Consistent with the higher value of falls per person-year, the online survey also shows a significantly higher overall number of falls per distance cycled (5.7 falls per 10,000 km with 95% CI [5.4, 6.0]). Despite these differences, these risks are roughly in the range of 1.5 to 12.9 falls per 10,000 km cycled known in the literature (Aultman-Hall & Hall, 1998; Aultman-Hall & Kaltenecker, 1999; de Geus et al., 2012).

The risk of falling as a cyclist in other weather conditions is 0.5 (95% CI [0.3, 0.7]) and 0.5 (95% CI [0.4, 0.6]) falls per 10,000 km based on the field surveys conducted during times of snow/ice and other weather conditions, respectively. The online survey shows a significantly higher risk of falling for cyclists in other weather conditions with 2 falls per 10,000 km (95% CI [1.9, 2.1]).

Significantly higher risks were calculated for cyclist falls in snowy/icy conditions. We calculated an average of 16 falls per 10,000 km cycled in snowy/icy conditions (95% CI [10.9, 21.1])

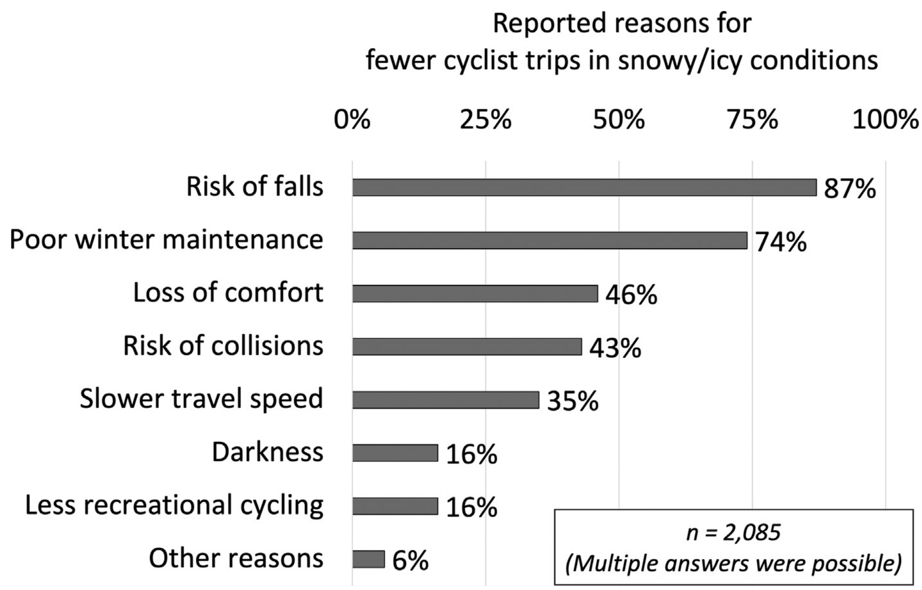

Fig. 5. Reasons for fewer cyclist trips in snowy/icy conditions reported in online survey.

Table 1
Results of manual cyclist counts in different weather conditions by city, area, and section.

City	Area	Section	Duration [min]	Cyclists counted: Other Weather	Cyclists counted: Snow/Ice	Delta
Aachen	Lothringer Staße	A	90	123	33	−73%
		B	90	171	31	−82%
	Vaalser Straße	A	45	51	26	−49%
		B	120	65	30	−54%
Dresden	Ammonstraße	A	315	218	56	−74%
		B	150	60	12	−80%
		C	180	72	19	−74%
	Bergstraße	A	150	59	26	−56%
		B	180	58	15	−74%
	Liebigstraße	A	75	89	34	−62%
	Zellescher Weg	A	75	324	38	−88%
		B	90	282	40	−86%
Münster	Neutor	A	45	406	355	−13%
		B	45	228	180	−21%

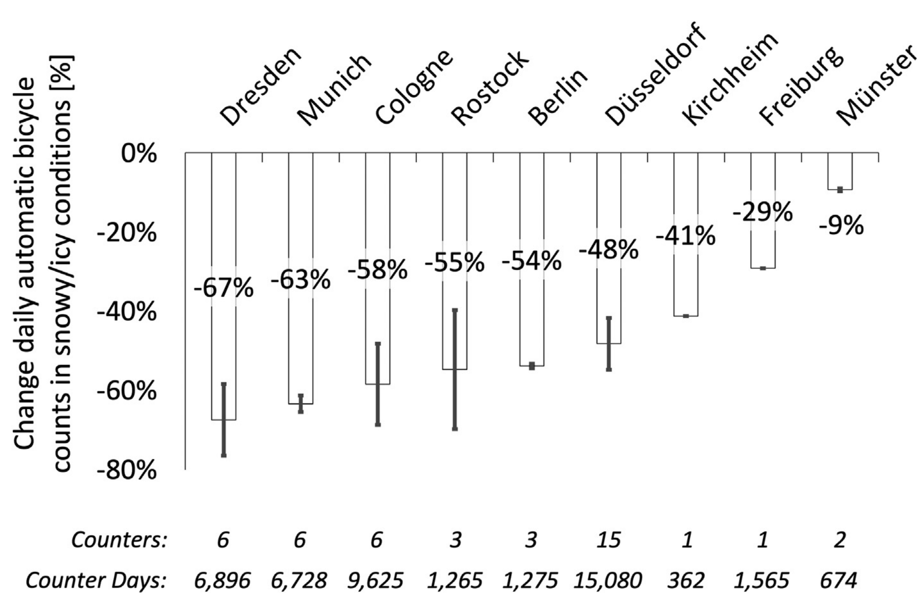

Fig. 6. Change in daily automatic bicycle counts in snowy/icy conditions by city.

from the field surveys conducted in times of snow or ice and an average of 9.5 falls per 10,000 km cycled in snowy/icy conditions (95% CI [6.8, 12.2]) from the field surveys conducted in times with other weather conditions. From the online survey, we calculate an average of 76.5 falls per 10,000 km cycled in snowy/icy conditions (95% CI [65.3, 87.7]).

Based on the field survey conducted during times of snow or ice, we see significantly higher risks for cyclist falls in snowy/icy conditions among respondents aged 18 to 44 compared to those aged 45 to 64. Beyond that, no statistically significant differences by age or gender are found for any of the absolute risks calculated from any of the surveys. It must be noted that for respondents aged 65 or older the sample is comparably sparse, thus causing high uncertainties. Fig. 7 shows the risk of cyclist falls according to the three different surveys.

Results from all three surveys show a significantly higher average fall risk for bicyclists in snowy/icy conditions than in other weather conditions. However, the main differences in the magnitudes of the estimated risk ratios (RR) are not between online and field surveys, as this is the case with the total falls per distance travelled, but between the weather conditions at the time of the field surveys: The average RR based on the online survey is 38 (95% CI [32, 44]) and based on the field survey conducted during times of snow or ice it is 36 (95% CI [19, 53]), while it is 20 (95% CI [13, 27]) based on the field survey conducted during other weather. There is a tendency of lower risk ratios among respondents aged 45 and older, but these differences are not statistically significant. Overall, no statistical differences regarding age or gender are found for the RR of falls in snowy/icy versus other conditions. The estimated RR are shown in Table 2.

Regardless of the survey method and the weather situation during the survey, the severity of injury, both in terms of medical treatment in general and hospitalization in particular, is on average significantly lower for the respondents' most recent cyclist falls in snowy/icy conditions than for the most recent falls in other weather conditions. Depending on the survey method, 8 to 14% of respondents reported medical treatment after their last cyclist fall during snowy/icy conditions, while 25 to 33% reported this for their last cyclist fall in other weather conditions. Hospitalization after their last cyclist fall during snowy/icy conditions was reported by 1 to 4% of the respondents and after their last cyclist fall in other weather conditions by 8 to 19% of them. Of these, more than 24 hours of hospitalization were reported for less than 1% of the most recent cyclist falls during snowy/icy conditions and for 4 to 8% of the most recent cyclist falls in other weather conditions.

For the results on the injury severity of the last cyclist fall in snowy/icy conditions, there are no statistically significant differences between the survey methods. For the respective last cyclist fall during other weather conditions, there are no statistically significant differences between the survey methods regarding general medical treatment. However, in terms of general hospitalization and hospitalization for over 24 hours, there are statistically significant differences between online and field surveys as well as between the weather conditions at the time of the surveys. The injuries and injury severities suffered from cyclist falls are shown in Fig. 8.

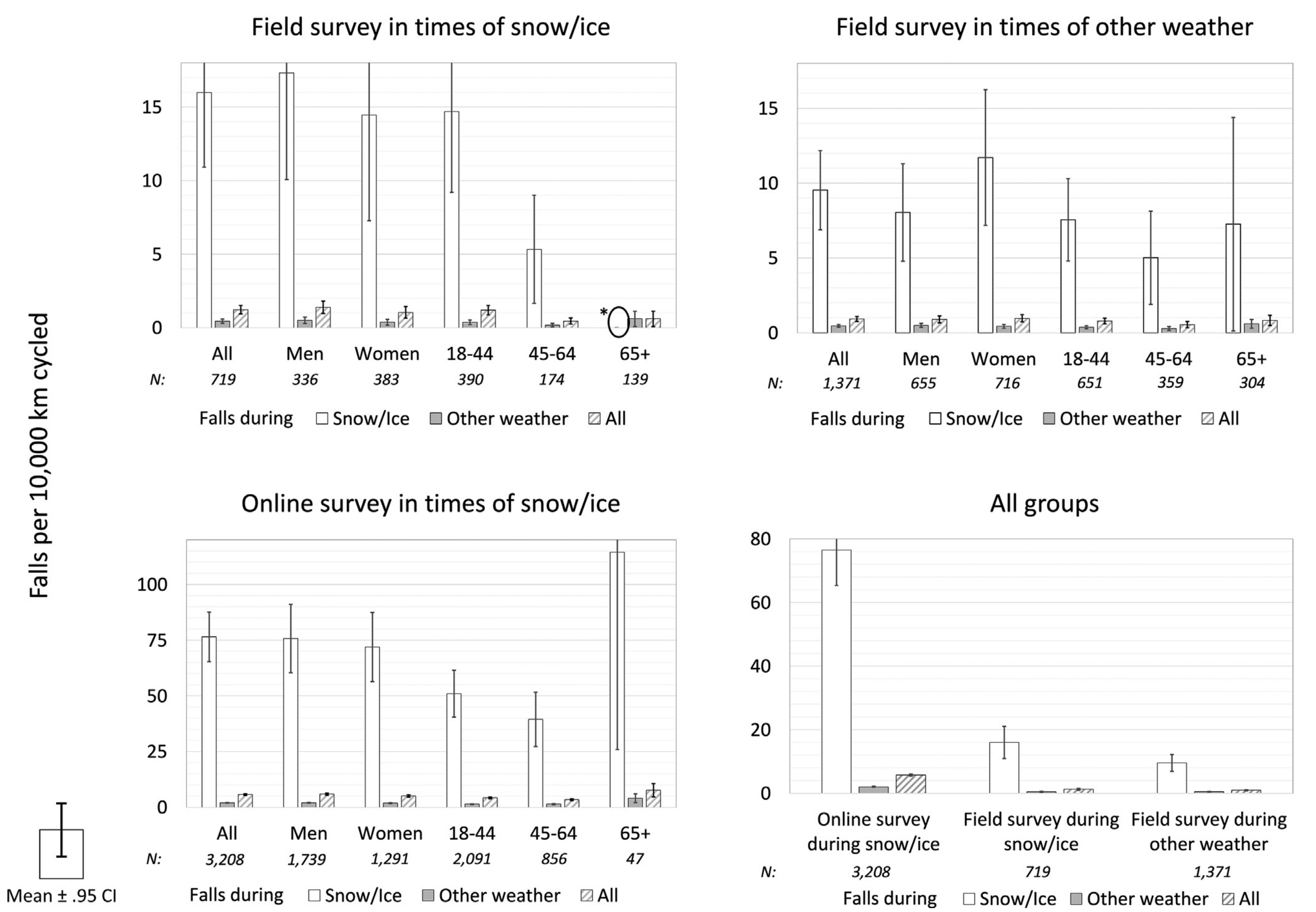

Fig. 7. Falls per 10,000 km cycled in different weather conditions by survey method, gender, and age. Top left: Field survey conducted in times of snow/ice. Top right: Field survey conducted during other weather. Bottom left: Online survey conducted in times of snow/ice. Bottom right: All surveys methods (*No data about falls during snow/ice).

Table 2
Risk Ratios (RR) for cyclist falls in snowy/icy conditions by survey method, gender, and age.

	Risk Ratios (RR) for cyclist falls in snowy/icy conditions		
	Field surveys		Online survey
	During other weather	During snow/ice	During snow/ice
All	20.2 (±06.9)	35.9 (±16.5)	37.7 (±06.1)
Men	16.0 (±07.8)	34.2 (±20.5)	36.8 (±08.2)
Women	26.9 (±12.8)	38.1 (±27.6)	38.3 (±09.3)
18–44	20.0 (±09.0)	38.9 (±21.4)	35.8 (±08.1)
45–64	17.1 (±12.9)	30.7 (±30.7)	27.5 (±09.3)
65+	12.0 (±13.1)	–*	28.0 (±25.5)

Fig. 9 shows the proportions of the types of medical treatment by weather conditions at the time of the last cyclist fall of the respondents and by their age (summed over all surveys). For all age groups, the injury severity (both in terms of hospitalization and in terms of medical treatment at all) is reduced for falls in snowy/icy conditions compared to those in other weather conditions. This difference is significant within the age groups 18–24, 25–44, and 45–64 but not for the age group 65+. The sample size for this highest age group is small and only allows for tentative interpretation but overall, there is a tendency of a higher proportion of falls with hospitalization in this age group.

Ninety percent of the respondents' most recent cyclist crashes in snowy/icy conditions were neither reported to the police nor to an insurer, while this level of underreporting is 77% for the most recent cyclist crashes during other weather conditions. Both the respondents' most recent falls in snowy/icy conditions and those during other weather conditions, when reported, were almost exclusively reported to insurers. Thus, 9% of the respective last falls in snowy/icy conditions were reported to insurers compared to 23% of the respective last falls during other weather conditions. Less than 1% of all falls were reported to the police. The differences by weather in reporting shares between the respective last falls in snowy/icy versus other weather conditions are statistically significant. For the respondents' most recent falls in both snowy/icy and other weather conditions, proportions of medical treatment and reporting to police or insurer correlate with high statistical significance. A few respondents stated that they reported their most recent cyclist fall to a department in the municipality. The extent of underreporting of cyclist falls is shown in Table 3.

4. Discussion

4.1. Distances traveled by bicycle

In this study, the analysis of HTS data (Ahrens et al., 2014) showed a statistically significant decrease of 53% (95% CI [45, 61]) in the total distance travelled per person and day for snowy/icy days compared to days with other weather conditions. Due to the lack of equivalent studies, only approximate comparisons with results from the literature are reasonable: Bergström and Magnusson (2003) found a decrease in the number of bicycle trips per person and day of 47%, which is of a similar magnitude. Here, however, the information on how the average trip distances changed is missing for a conclusive comparison. Böcker and Thorsson (2014) found a more moderate decrease in both the number of trips and the hours spent cycling on a snowy day of 24 to 32% and 24 to 34%, respectively, compared to our results. It is notable that the multivariate models they fitted also include other independent variables such as temperature, rainfall, and wind speed. For a conclusive comparison, however, the information on possible changes in average cycling speed on snowy days is missing. In this context, Bärwolff et al. (2022) conducted cycling speed measurements on sidewalks. In downhill sections, they found significantly lower cycling speeds on snowy sidewalks compared to dry sidewalks, but no such differences on flat and uphill sidewalks. Other studies by Durth et al. (1993), Zhao et al. (2018) and An et al. (2019) showed substantially greater decreases of 75–90% in cyclist volumes or trips on snowy or icy days.

In this study, further data sources were analyzed to validate the distances cycled based on the HTS. Although the manual and automatic bicycle count data show the traffic volume at a cross-section, it implicitly includes the travel distance in addition to the trip frequency, since longer bicycle trips are more likely to pass the counter and are more likely to be detected by it than shorter bicycle trips. The manual bicycle counts show a mean decrease of 63%, which also generally confirms the decrease in distances cycled from the HTS. However, the decreases in the number of bicycles counted in snowy/icy conditions vary considerably between the three cities analyzed and these are not representative for all German cities. Due to the larger number of cities and their distribution over the German territory, the analysis of the automatic bicycle counters is considered to be more representative compared to the manual counts. This analysis shows an average decrease in bicycle traffic of 53% on days with snowy/icy conditions compared

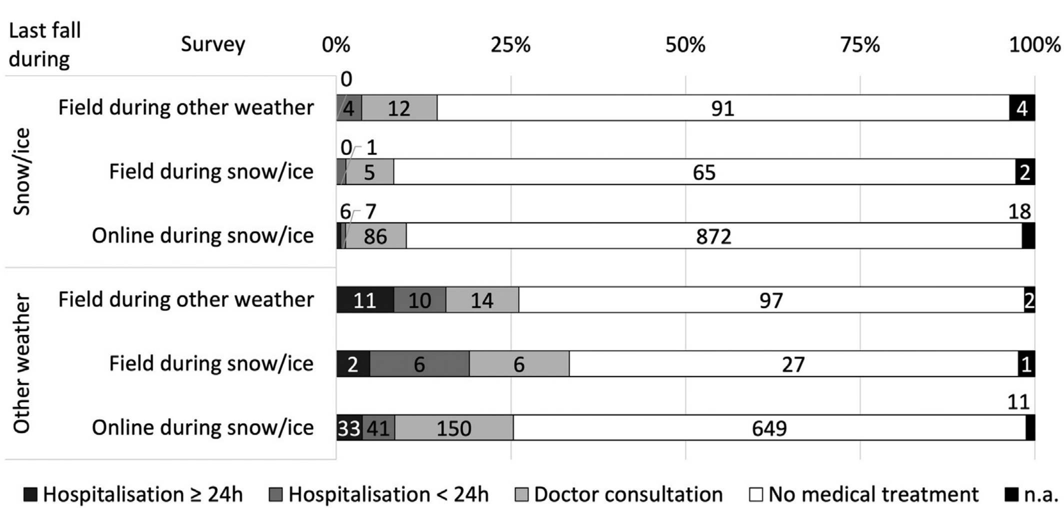

Fig. 8. Intensity of medical treatment after respondents respective last fall by weather conditions and survey method.

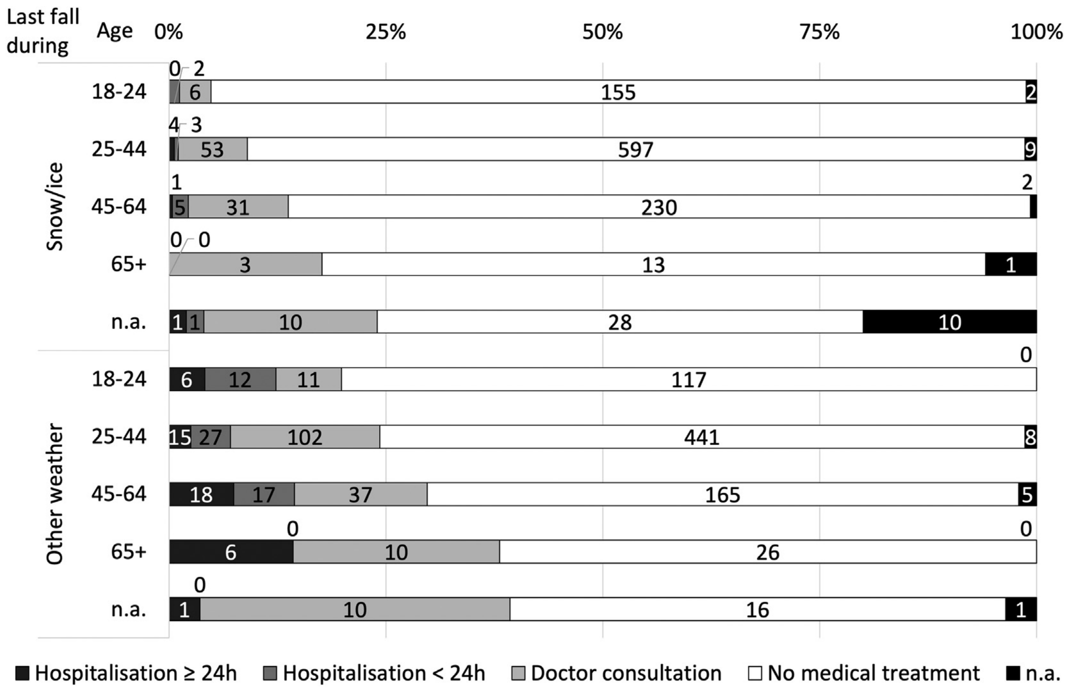

Fig. 9. Intensity of medical treatment after respondents respective last fall by weather conditions and age.

Table 3
Reporting of online respondents respective last fall by weather conditions.

	Last fall reported to					
Last fall during	Police only	Police + insurer	Insurer only	None	n.a.	Total
Snow/ice	1 (0%)	5 (1%)	77 (8%)	890 (90%)	16 (2%)	989 (100%)
Other weather	6 (1%)	32 (4%)	153 (17%)	684 (77%)	9 (1%)	884 (100%)

to days with other conditions. This decrease is larger in cities with comparatively low overall cycling mode shares like Dresden (18% as of 2018) and Munich (18% as of 2017) and smaller in cities with comparatively high overall cycling mode shares like Freiburg (34% as of 2017) and Münster (44% as of 2019). It seems that where many trips are usually made by bicycle, the cyclist volumes remain stable even in snowy/icy conditions. This is in line with recent findings from Böcker et al. (2019) and Hudde (2023), according to which the drop in cycling in the Netherlands with its comparably high cycling modal share is significantly lower than in Sweden, Norway, or Germany. This is also confirmed by the results of our online survey, according to which respondents who cycle daily or almost daily in summer also continue this behavior in snowy/icy conditions, while respondents who do not cycle on a daily basis in summer tend to avoid cycling altogether or cycle far less frequently in snowy/icy conditions. Possible explanations for that could be a higher share of utilitarian cycling and a lower share of car ownership among frequent cyclists.

In addition, the online survey shows an overall average decrease of 59% in the number of days cycled on snowy/icy days compared to other weather conditions, which points in the same direction as the overall decrease in the average distance cycled per HTS respondent. It should be mentioned here that the number of days with bicycle use is only to a limited extent comparable with the average distance traveled by bicycle due to the lack of information on trip frequency and length.

In the online survey, most respondents also reported that the risk of falling, and the insufficient clearing and gritting conditions discourages them from winter cycling. This was mentioned more frequently than loss of comfort. We cannot exclude a bias by selection or a social desirability bias in these statements, as the online survey was published under the title "Traffic behaviour and risk of falling in snow and icy conditions."

4.2. Risk of falling with a bicycle

The overall risks of cyclist falls calculated in this study roughly line up with the values known from the literature. However, similar to the distance traveled by bicycle, no values are known from the literature for cyclists' risk of falling per distance cycled in snowy/icy conditions. Previous studies have found that slipping on snow or ice accounts for a significant proportion of cyclist falls, without considering variations in their exposure to these weather conditions. This is probably due to missing data or study designs in which snow and ice are one of many independent variables.

Taking exposure from HTS into consideration, dependent on the survey method we find average risks of cyclist falls from 9.5 up to 76.5 falls per 10,000 km cycled in snowy/icy conditions. Compared to the risks of cyclist falls in other weather conditions, we derive RRs of 20 to 38 for cycling in snowy/icy conditions that apply almost equally to all genders and age groups. This means that a cyclist in snowy/icy conditions has a 20–38 times higher risk of falling than when covering the same distance in other weather conditions.

On the other hand, we find fewer injuries among reported cyclist falls during snowy/icy conditions compared to those during other conditions. Depending on the survey method, 8–14% of the respondents reported medical treatment after their last cyclist fall during snowy/icy conditions, while 25 to33% reported this for their last cyclist fall in other weather conditions. This difference is also significant within the age groups 18–24, 25–44, and 45–64, but not within the 65+ age group (due to the small sample size). Considering both the increased risk of falling and the lower probability of injury in the event of a fall, a significantly increased overall distance-based risk of being injured is still to be expected on days with snowy/icy conditions.

A possible reason for the increased risk of falling in snowy/icy conditions is the condition of the surface itself (lack of winter maintenance) in combination with unsuitable equipment (no spikes) and possibly little experience (because snow/ice occurs relatively rarely in Germany). An explanation for the lower injury severity in case of a fall in snowy/icy conditions could be lower speeds and a generally more careful riding style.

The proportion of cyclist falls reported to insurers is lower for falls during snowy/icy conditions compared to other weather conditions and strongly correlated with the proportion of injuries. In contrast to that, 99% of the cyclist falls in snowy/icy conditions and 95% of cyclist falls in other weather conditions are not reported to the police.

Similar fall rates per person-years in our field survey and in a Danish follow-up study by Olesen et al. (2021) show the general applicability of retrospective surveys. However, the overall fall rates reported online were around five times higher than those from the field survey. We suspect a non-response bias as the reason for this difference, since due to the topic of the online survey (winter service on sidewalks and cycle paths) more active cyclists may have participated, among them probably especially those with many experienced falls in snowy/icy conditions. We do not suspect this bias in the results of the field surveys because the respondents did not know the topic when they agreed to participate in the survey. On the other hand, the five-year period for retrospective reporting of the number of falls may have led to some underreporting due to memory lapses, which would be expected in both online and field surveys.

In contrast to the discrepancy between online and field survey regarding the reported absolute fall rates, the RRs for falls in snowy/icy compared to other weather conditions from the online survey and from the field survey conducted at times of snow or ice is almost identical. That said, there is a considerably lower RR among all groups based on the field survey conducted at times of other weather conditions. Since the online survey was also conducted in weeks when there was snow and ice, we suppose that when snow/ice is present, more cyclists who experienced falls in snowy/icy conditions were willing to respond to our survey. We also assume that falls in snowy/icy conditions are more likely to be recalled when asked in wintertime, which explains the higher RRs derived from the online survey and the on-site survey conducted in such weather.

5. Summary

In line with the literature, we found significant decreases in cycling volumes in snowy/icy conditions from multiple data sources and that the risk of falls and inadequate winter maintenance are critical reasons for this. Our results and those of other studies show that in regions with a higher cycling share, the decrease in winter cycling is lower than in regions with a lower cycling share. This suggests that the promotion of cycling in general could be accompanied by an even stronger increase in winter cycling. In this study, we estimate the risk of falling per distance cycled differentiated by snowy/icy and other weather conditions for the first time. This distance-based risk for cyclist falls is substantially higher in snowy/icy compared to other conditions. However, in the event of a fall in snowy/icy conditions, cyclists suffer fewer consequences on average than in other weather. This decrease in injury consequences per fall is not sufficient to outweigh the increased risk of falling in the first place: Overall we estimate more injuries in snowy/icy conditions than in other conditions. Increased cycling in winter is therefore likely to lead to an even higher absolute number of injuries caused by cyclist falls, but improved winter maintenance has the potential to mitigate this. And it has the potential to further increase winter cycling.

It is debatable if this topic will still be relevant in the future (e.g., in Central Europe) because of advancing global warming, or whether the associated extreme weather events will continue to provide snowy/icy surfaces on cycling facilities on a regular basis. In any case, this topic will remain a large issue in Scandinavia and Canada with their subarctic climate, where snowy/icy conditions will continue to prevail on many days of the year. On the other hand, the current high risk of cyclist falls on snowy/icy days can be a barrier to increasing the cycling mode share, which may have an impact beyond the winter.

Furthermore, this study once again shows the high proportion of unreported cyclist falls. From the data analyzed we are confident that field surveys are suitable for representative samples in contrast to online surveys. Besides the problem of representing the demographics of the population, the topic and the time of the survey have a major influence on the non-response bias, which in the case of the distance-based risks in this study is almost of one order of magnitude.

Future studies could validate these findings in other regions, focus on the impact of winter maintenance and on the interaction of perceived comfort and safety in terms of winter cycling mode shares based on descriptive and model-based statistical methods.

6. Practical applications

The results of this study show that improved winter maintenance has the potential to not only reduce the risk of falls, but also encourage winter cycling. This is a suitable basis for decision-makers to weigh the need for countermeasures such as improved winter service.

The very high level of underreporting in this study shows that police statistics are rather impractical for researching cyclist falls and reinforces the need to improve the reporting of falls and SBCs by cyclists to insurers and the police.

The findings from the study design consisting of several retrospective surveys conducted during different weather conditions in the field as well as online provide helpful insight into the extent of survey effects, which can be taken into consideration when designing future studies.

Funding

This work was supported by the German Federal Highway Research Institute [grant FE 89.0308/2015].

CRediT authorship contribution statement

Martin Bärwolff: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. **Regine Gerike:** Conceptualization, Resources, Project administration, Supervision, 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 like to thank BSV Büro für Stadt- und Verkehrsplanung Aachen Dr.-Ing. Reinhold Baier GmbH and our student workers for supporting data collection and our colleagues for professional advice.

References

Ahrens, G.-A., Ließke, F., Wittwer, R., Hubrich, S., & Wittig, S. (2014). *Tabellenbericht zum Forschungsprojekt 'Mobilität in Städten – SrV 2013' in der Landeshauptstadt Dresden*. Lehrstuhl Verkehrs- und Infrastrukturplanung: Technische Universität Dresden.

Ahrens, G.-A., Wittwer, R., Hubrich, S., Wittig, S., & Ließke, F. (2015). *Sonderauswertung zum Forschungsprojekt 'Mobilität in Städten—SrV 2013'*. Stadtgruppe: SrV-Städtepegel. Technische Universität Dresden, Lehrstuhl Verkehrs- und Infrastrukturplanung.

An, R., Zahnow, R., Pojani, D., & Corcoran, J. (2019). Weather and cycling in New York: The case of Citibike. *Journal of Transport Geography, 77*, 97–112. https://doi.org/10.1016/j.jtrangeo.2019.04.016.

Aultman-Hall, L., & Hall, F. L. (1998). Ottawa-Carleton commuter cyclist on-and off-road incident rates. *Accident Analysis & Prevention, 30*(1), 29–43. https://doi.org/10.1016/S0001-4575(97)00059-6.

Aultman-Hall, L., & Kaltenecker, M. G. (1999). Toronto bicycle commuter safety rates. *Accident Analysis & Prevention, 31*(6), 675–686. https://doi.org/10.1016/S0001-4575(99)00028-7.

Bärwolff, M., Reinartz, A., & Gerike, R. (2022). Correlates of pedestrian and cyclist falls in snowy and icy conditions. *Transactions on Transport Sciences, 12*(3), 67–77. https://doi.org/10.5507/tots.2021.007.

Bergström, A. (2002). *Winter maintenance and cycleways* PhD thesis. Stockholm, Sweden: Royal Insitute of Technology.

Bergström, A., & Magnusson, R. (2003). Potential of transferring car trips to bicycle during winter. *Transportation Research Part A: Policy and Practice, 37*(8), 649–666. https://doi.org/10.1016/S0965-8564(03)00012-0.

Böcker, L., Dijst, M., & Prillwitz, J. (2013). Impact of everyday weather on individual daily travel behaviours in perspective: A literature review. *Transport Reviews, 33*(1), 71–91. https://doi.org/10.1080/01441647.2012.747114.

Böcker, L., Priya Uteng, T., Liu, C., & Dijst, M. (2019). Weather and daily mobility in international perspective: A cross-comparison of Dutch, Norwegian and Swedish city regions. *Transportation Research Part D: Transport and Environment, 77*, 491–505. https://doi.org/10.1016/j.trd.2019.07.012.

Böcker, L., & Thorsson, S. (2014). Integrated weather effects on cycling shares, frequencies, and durations in Rotterdam, the Netherlands. *Weather, Climate, and Society, 6*(4), 468–481. https://doi.org/10.1175/WCAS-D-13-00066.1.

Brandenburg, C., Matzarakis, A., & Arnberger, A. (2007). Weather and cycling – A first approach to the effects of weather conditions on cycling. *Meteorological Applications, 14*(1), 61–67. https://doi.org/10.1002/met.6.

Buehler, R., & Pucher, J. (2017). Trends in walking and cycling safety: Recent evidence from high-income countries, with a focus on the United States and Germany. *American Journal of Public Health, 107*(2), 281–287. https://doi.org/10.2105/AJPH.2016.303546.

de Geus, B., Vandenbulcke, G., Int Panis, L., Thomas, I., Degraeuwe, B., Cumps, E., Aertsens, J., Torfs, R., & Meeusen, R. (2012). A prospective cohort study on minor accidents involving commuter cyclists in Belgium. *Accident Analysis & Prevention, 45*, 683–693. https://doi.org/10.1016/j.aap.2011.09.045.

de Kruijf, J., van der Waerden, P., Feng, T., Böcker, L., van Lierop, D., Ettema, D., & Dijst, M. (2021). Integrated weather effects on e-cycling in daily commuting: A longitudinal evaluation of weather effects on e-cycling in the Netherlands. *Transportation Research Part A: Policy and Practice, 148*, 305–315. https://doi.org/10.1016/j.tra.2021.04.003.

Deutscher Wetterdienst (2018). *Weather data obtained from Deutscher Wetterdienst—DWD WESTE-XL*. https://kunden.dwd.de/weste/xl_login.jsp.

Durth, W., Hiersche, E.-U., Lamm, R., et al. (1993). *Winterdienst auf Radwegen. Schlussbericht zum Forschungsauftrag FE 77329/90 des Bundesministers fuer Verkehr*.

Eriksson, J., Niska, A., & Forsman, Å. (2022). Injured cyclists with focus on single-bicycle crashes and differences in injury severity in Sweden. *Accident Analysis & Prevention, 165*. https://doi.org/10.1016/j.aap.2021.106510 106510.

Feleke, R., Scholes, S., Wardlaw, M., & Mindell, J. S. (2018). Comparative fatality risk for different travel modes by age, sex, and deprivation. *Journal of Transport & Health, 8*, 307–320. https://doi.org/10.1016/j.jth.2017.08.007.

Fieller, E. C. (1940). The biological standardization of insulin. *Supplement to the Journal of the Royal Statistical Society, 7*(1), 1. https://doi.org/10.2307/2983630.

Flynn, B. S., Dana, G. S., Sears, J., & Aultman-Hall, L. (2012). Weather factor impacts on commuting to work by bicycle. *Preventive Medicine, 54*(2), 122–124. https://doi.org/10.1016/j.ypmed.2011.11.002.

Fournier, N., Christofa, E., & Knodler, M. A. (2019). A mixed methods investigation of bicycle exposure in crash rates. *Accident Analysis & Prevention, 130*, 54–61. https://doi.org/10.1016/j.aap.2017.02.004.

Gerike, R., Hubrich, S., Koszowski, C., Schröter, B., & Wittwer, R. (2021). In *Active transport: Heterogeneous street users serving movement and place functions* (pp. 140–146). Elsevier. https://doi.org/10.1016/B978-0-08-102671-7.10418-X.

Girod, B. (2005). Eigenschaften des Fahrradverkehrs. Analyse des Fahrradverkehrs aufgrund der Mikrozensus 2000 und Thurgau 2003 Verkehrsbefragungen. http://www.ivt.ethz.ch/docs/students/sa134.pdf.

Griessbach, A. (2008). *Wetterabhängigkeit derVerkehrsmittelnutzung in Dresden* [Thesis]. TU Dresden.

Hoffman, M. R., Lambert, W. E., Peck, E. G., & Mayberry, J. C. (2010). Bicycle commuter injury prevention: It is time to focus on the environment. *Journal of Trauma: Injury, Infection & Critical Care, 69*(5), 1112–1119. https://doi.org/10.1097/TA.0b013e3181f990a1.

Hudde, A. (2023). It's the mobility culture, stupid! Winter conditions strongly reduce bicycle usage in German cities, but not in Dutch ones. *Journal of Transport Geography, 106*. https://doi.org/10.1016/j.jtrangeo.2022.103503 103503.

Liu, C., Susilo, Y. O., & Karlström, A. (2015). The influence of weather characteristics variability on individual's travel mode choice in different seasons and regions in Sweden. *Transport Policy, 41*, 147–158. https://doi.org/10.1016/j.tranpol.2015.01.001.

Miranda-Moreno, L. F., Nosal, T., Schneider, R. J., & Proulx, F. (2013). Classification of bicycle traffic patterns in five north American cities. *Transportation Research Record: Journal of the Transportation Research Board, 2339*(1), 68–79. https://doi.org/10.3141/2339-08.

Niska, A., & Eriksson, J. C. (2013). *Statistik över cyklisters olyckor: Faktaunderlag till gemensam strategi för säker cykling*.

Ohlin, M., Algurén, B., & Lie, A. (2019). Analysis of bicycle crashes in Sweden involving injuries with high risk of health loss. *Traffic Injury Prevention, 20*(6), 613–618. https://doi.org/10.1080/15389588.2019.1614567.

Olesen, A. V., Madsen, T. K. O., Hels, T., Hosseinpour, M., & Lahrmann, H. S. (2021). Single-bicycle crashes: An in-depth analysis of self-reported crashes and estimation of attributable hospital cost. *Accident Analysis & Prevention, 161*. https://doi.org/10.1016/j.aap.2021.106353 106353.

Schepers, P., Stipdonk, H., Methorst, R., & Olivier, J. (2017). Bicycle fatalities: Trends in crashes with and without motor vehicles in The Netherlands. *Transportation Research Part F: Traffic Psychology and Behaviour, 46*, 491–499. https://doi.org/10.1016/j.trf.2016.05.007.

Schiller, C., Zimmermann, F., & Bohle, W. (2011). *Hochrechnungsmodell von Stichprobenzählungen für den Radverkehr*. TU Dresden. Professur für Straßenverkehrstechnik mit Fachbereich Therie der Verkehrsplanung.

Thomas, T., Jaarsma, R., & Tutert, B. (2013). Exploring temporal fluctuations of daily cycling demand on Dutch cycle paths: The influence of weather on cycling. *Transportation, 40*(1), 1–22. https://doi.org/10.1007/s11116-012-9398-5.

Utriainen, R. (2020). Characteristics of commuters' single-bicycle crashes in insurance data. *Safety, 6*(1), 13. https://doi.org/10.3390/safety6010013.

Yiannakoulias, N., Bennet, S. A., & Scott, D. M. (2012). Mapping commuter cycling risk in urban areas. *Accident Analysis & Prevention, 45*, 164–172. https://doi.org/10.1016/j.aap.2011.12.002.

Zhao, J., Wang, J., Xing, Z., Luan, X., & Jiang, Y. (2018). Weather and cycling: Mining big data to have an in-depth understanding of the association of weather variability with cycling on an off-road trail and an on-road bike lane. *Transportation Research Part A: Policy and Practice, 111*, 119–135. https://doi.org/10.1016/j.tra.2018.03.001.

Martin Bärwolff is a research associate at the Chair of Integrated Transport Planning and Traffic Engineering at Technische Universität Dresden (TUD). After studying traffic engineering in Dresden, he is now a PhD student, and co-founded platomo, a start-up specialised in the development of hardware, software and automated methods for data-driven analysis and modelling of traffic and mobility. His research interests focus on traffic safety in general as well as traffic behaviour of vulnerable road users and automated methods to measure and analyse traffic and mobility.

Prof. Dr.-Ing. Regine Gerike is head of the Chair of Integrated Transport Planning and Traffic Engineering at TUD. Before joining TUD, she chaired the Institute for Transport Studies at the University of Natural Resources and Life Sciences (BOKU) in Vienna, Austria. From 2008 to 2012 she was assistant professor at Technische Universität München, head of the Research centre mobility and transport and of the PhD-program "mobil.LAB Sustainable Mobility in the Metropolitan Region of Munich". Her research interests include transport planning and traffic safety with a focus on vulnerable road users.