TSR TRAFFIC SAFETY RESEARCH
AN INTERDISCIPLINARY JOURNAL

Research article

Pedestrians travel distances and risk of falls in snowy and icy conditions in German cities

Martin Bärwolff[1,2]*, **Regine Gerike**[1]

[1]TUD Dresden University of Technology, Germany

[2]Autobahn GmbH, Germany

*Corresponding author: martin.baerwolff@tu-dresden.de

Handling editor: **Aliaksei Laureshyn**, Lund University, Sweden

Reviewers: **Glenn Berggård**, Luleå University of Technology, Sweden
Torkel Bjørnskau, Institute of Transport Economics, Norway

Received: 1 May 2024; Accepted: 12 August 2024; Published: 27 September 2024

Abstract: Walking as a sustainable, space-efficient and generally healthy mode of transport is promoted throughout the whole year. However, only a few studies provide findings on the impact of snowy or icy surfaces on pedestrian's volumes and their risk of falls, especially in central Europe. To address this gap, multiple data sources have been analysed: travel diaries of 22 772 respondents to a recurring German Household Travel Survey, information on travel behavior and experienced pedestrian falls of 3 333 respondents to additional dedicated online and field surveys as well as manual counts from 65 hours of video footage collected at 13 sites. Depending on the data source, no changes or slight increases in pedestrian traffic have been found in snowy/icy conditions. We determined a risk of at least 7.8 falls per 10 000 km walked in snowy/icy conditions, which is about 32 times higher compared to other weather conditions. However, the overall share of medical treatment did not differ significantly by weather condition. Pedestrians aged 65 and older tend to have a lower overall risk of falls but are more likely to receive medical treatment in case of a fall. The calculated risk of falls differs greatly depending on survey type (online vs field) and timing (during snow/ice vs during other weather). Including pedestrian stages of Public Transport and Motorized Individual Transport trips significantly influences the study results and we assume leads to more realistic results. While pedestrian falls are generally not recorded by the police, only those that caused medical treatment were reported to insurers. The findings underline the importance of winter maintenance on pedestrian facilities to promote walking throughout the whole year.

Keywords: distance walked, injury severity, pedestrian injury, pedestrian safety, single pedestrian accidents, survey effects, winter walking

1 Introduction

Walking as a mode of transport comes with various benefits. It is space-efficient and causes low individual and societal costs; it is flexible and, in combination with public transport, it can cover almost all mobility needs (Koszowski et al., 2019). The promotion of walking also aids in increasing physical activity levels with positive impacts on public health and supporting the targets for physical activity formulated by the World Health Organization (Bull et al., 2020). Achieving high pedestrian volumes in lively streets and public spaces is a core ambition in urban planning and increases the quality of life and the economic success of cities (Sim & Gehl, 2019).

At the same time, pedestrians, together with cyclists and further users of micromobility vehicles, are the most vulnerable road users (VRUs). They have a raised risk per travelled distance of getting involved in an accident or fall compared to users of the motorized

transport modes and, in addition, the consequences are on average more severe (Aldred, 2018; Feleke et al., 2018; Elvik & Bjørnskau, 2019).

Studies showed that pedestrians are more likely to experience a fall than to be involved in a collision with a vehicle (Schepers et al., 2017; Elvik & Bjørnskau, 2019). Furthermore, almost as many pedestrian injuries are caused by falls as by collisions with vehicles (Eilert-Petersson & Schelp, 1998), and among older people they even account for the greater proportion of injuries (Naumann et al., 2011). A few studies indicate that slippery snow and ice lead to an increased number of falls by pedestrians in almost every winter (Öberg et al., 1996; Furian et al., 2011; Elvik & Bjørnskau, 2019). Accordingly, there seems to be a great macro-economic potential in preventing pedestrian falls in snowy/icy conditions.

On the other hand, much less research has been conducted on pedestrian falls than on accidents between vehicles and pedestrians. This is in large part due to severe underreporting of VRU's single accidents in official databases, particularly for those resulting only in slight or no injuries (Bärwolff & Gerike, 2023). Moreover, pedestrian falls are by definition not included in official traffic accident statistics as these require the involvement of at least one moving vehicle (ERSO, 2023). Even though Methorst et al. (2017) proposed to add them to the official definition of traffic accidents, current research on pedestrian falls still needs complementary research approaches e.g. based on surveys, on data from insurers or from hospital emergency departments.

So far, only a few studies have been found that quantify the risk of pedestrian falls based on snowy/icy surfaces compared to wet or bare surfaces considering the distances travelled in such conditions. Our article aims at closing this gap.

2 Literature

2.1 Travel behaviour

Studies on changes in pedestrian volumes in different weather conditions showed different effects. There are studies that found slightly increasing pedestrian volumes in snowy winter weather (Sabir, 2011; Liu et al., 2015); other studies found decreasing pedestrian volumes in these situations (Aultman-Hall et al., 2009; Miranda-Moreno & Lahti, 2013). Based on count data for one single location in Vermont (U.S.), Aultman-Hall et al. (2009) showed decreases in pedestrian volumes in winter months by approximately 16 percent on working days and Saturday but find no significant differences on public holidays and Sundays. Miranda-Moreno & Lahti (2013) analysed count data from automatic counts of pedestrian volumes at five locations in Montreal and found lower pedestrian volumes in winter months on weekdays and on weekends with the elasticities being higher on weekends than on weekdays. An analysis of the 2007/2008 Scottish National Household Travel Survey (NTS) by Hong (2016) showed that seasonal effects on utilitarian walking are higher on inhabitants of rural areas than inhabitants of urban areas.

Precipitation decreased pedestrian volumes by five to 27 percent (Aultman-Hall et al., 2009; Miranda-Moreno & Lahti, 2013; Schneider et al., 2012). Öberg et al. (1996) registered no reduction in pedestrian volumes on sidewalks partially covered by snow or ice compared to dry conditions but a decrease of about 25 percent on sidewalks completely covered with snow or ice. Baier et al. (2009) found that during snow or ice the number of trips as pedestrians decreased by a third among older people. Creemers et al. (2015) found no effects of snow on mode choice behaviour but claimed this was due to rare occurrence of snow in their data set, the Dutch NTS of 2008. They also stated that findings on the impact of weather conditions on travel behavior depend on the granularity of the underlying weather data (hourly vs daily).

The effect of temperature on pedestrian volumes follows a bell-shaped function, very low and very high temperatures decrease pedestrian volumes (Aultman-Hall et al., 2009; Schneider et al., 2012; Miranda-Moreno & Lahti, 2013; Shaaban et al., 2018). Aultman-Hall et al. (2009), based on their pedestrian model for the noon peak hour, suggested that pedestrian volume increased by 1.5 percent for every degree centigrade. Öberg et al. (1996) showed that at temperatures below the freezing point, for every 5°C decrease in temperature, pedestrian volumes decreased by 10% to 15%. Schneider et al. (2012) found decreases in pedestrian volumes of appr. 10 percent in temperatures below 10°C and of appr. 11 percent in cloudy weather. Saneinejad et al. (2012) found that the proportion of pedestrians among commuters decreased below 5°C. Miranda-Moreno & Fernandes (2011) found decreases of pedestrian volumes of 22 percent in very warm weather > 30°C. Literature shows that weather conditions have larger impacts on

travel behaviour on mandatory activities like work or education than on leisure activities (Termida et al., 2018; Böcker et al., 2013; Cools et al., 2010). Also, it was shown that walking activities of older people and children are affected by weather conditions over-proportionally (Öberg et al., 1996; Baier et al., 2009).

Overall, walking is affected by weather conditions less than cycling (Bongiorno et al., 2019) and for pedestrian activities, built environment variables such as density and mixture of land-uses are far more important than weather variables (Miranda-Moreno & Lahti, 2013; Miranda-Moreno & Fernandes, 2011; Gascon et al., 2019). This is different for cycling where individual and household characteristics, socio-psychological variables, quality, and quantity of cycling facilities and the weather is more important than the built environment (Gao et al., 2018; Liu et al., 2017).

The literature found on pedestrian activity in different weather conditions are mainly based on count data, dedicated surveys, and Household Travel Survey (HTS) data. Count data are dependent on the specific study location and do not contain any explicit information on trip distances. Most of the studies based on dedicated surveys or HTS did not provide any information on the travel distances of pedestrians in different weather conditions. While only Sabir (2011) addressed travel distances, Gao et al. (2018) addressed travel times of pedestrians in different weather conditions.

2.2 Absolute risk of falls

Several studies have investigated the risk of pedestrian falls per distance walked, though some did not distinguish between individual pedestrian falls and incidents involving other road users (Feleke et al., 2018).

Among those making this distinction, Mindell et al. (2012) analysed data on hospital admissions and fatalities in England, utilizing distances travelled from Great Britain's NTS. While they calculated rates for pedestrian's 'on-highway incidents', including collisions, the paper provides enough information to compute injury and fatality rates for pedestrian falls. The results indicated 0.014 male and 0.006 female fatalities, along with 1.68 male and 1.8 female hospital admissions per million kilometers walked due to on-highway falls.

Oxley et al. (2018) focused on hospital admissions and emergency presentations in Victoria, Australia, resulting from falls on roads, streets, or highways. Distances walked were obtained from the HTS. The study reported 1.1 hospital admissions and 3.9 emergency department presentations per million kilometers walked among residents below the age of 75. For residents aged 75 and older, the figures rose to 25.5 hospital admissions and 15.0 emergency department presentations per million kilometers walked, with minimal differences in fall rates observed among age groups below 75.

Aldred (2018) utilized both falls and exposure data from the Great Britain NTS. The NTS asked about road accidents '*on a public road, including pavements and cycle lanes* […] *even if no other party were involved* […], *and about numbers of injuries*'. Their results allow the calculation of an overall injury rate due to pedestrian injuries of 2.4 per million miles, which translates to 1.5 injuries per million kilometers.

However, these studies generally lack differentiation based on weather or season. Two other studies specifically addressed the risk of falling on snow/ice per distance walked.

Eriksson & Sörensen (2015) examined injuries (MAIS 2+) resulting from pedestrian falls on snow/ice during winter in Sweden from 2011 to 2014. The data on falls were obtained from insurer's healthcare records. As a denominator, they used the distances walked from October to April obtained from the Swedish NTS. The results show a range of 1.1 (Göteborg) to 5.3 (Umeå) injuries per million kilometers walked, with relatively wide confidence intervals. Notably, women had twice the risk of injuries compared to men.

Elvik & Bjørnskau (2019) analysed injuries treated at the medical emergency clinic of Oslo after pedestrian falls in road space. Their study, related to travel data from NTS, revealed injuries per million kilometers walked: 15.6 for women and 12.1 for men throughout the year, escalating to 24.5 for women and 16.5 for men on snowy or icy surfaces.

Table 1 gives an overview of the fatality and injury rates due to pedestrian falls found in the literature.

Table 1 Fatality and injury rates due to pedestrian falls found in the literature

Study	Region	Data source	Definition of falls	Consequence	Subjects	Rate (per million km)
Mindell et al. (2012)	England	Falls: hospital study	On-highway pedestrian falls	Fatality	Women	0.006
					Men	0.001
		Distances: NTS		Hospital admission	Women	1.8
					Men	1.7
Oxley et al. (2018)	Victoria (Australia)	Falls: hospital study	Pedestrian falls on roads	Hospital admission	< 75	1.1
					75+	25.5
		Distances: HTS		Emergency department presentation	< 75	3.9
					75+	15.0
Aldred (2018)	Great Britain	Falls and distances: NTS	Single pedestrian accidents on a public roads	Injury	All	1.5
Eriksson & Sörensen (2015)	Sweden	Falls: insurer's healthcare records	Pedestrian falls on snow/ice	MAIS 2+ injuries	Göteborg	1.1
		Distances: NTS (Oct–Apr)			Umeå	5.3
Elvik & Bjørnskau (2019)	Oslo (Norway)	Falls: hospital study	Pedestrian falls in road space throughout the year	Medical emergency clinic presentation	Women	15.6
					Men	12.1
		Distances: NTS	Pedestrian falls in road space on snowy/icy surfaces	Medical emergency clinic presentation	Women	24.5
					Men	16.5

2.3 Relative risk of falls in different weather conditions

When determining relative risks for pedestrian falls in specific weather conditions, not only the number of falls should be considered, but also the exposure of pedestrians to these conditions. As this article focuses on the safety of the infrastructure, the distance travelled in the corresponding condition appears to be a suitable exposure. This implicitly also includes the proportion of time in which these conditions prevail.

The only study found comparing risks for pedestrian falls in winter or on snow/ice accounting for the distance travelled is Elvik & Bjørnskau (2019). Besides the absolute overall injury rate for pedestrian falls per distance walked mentioned above, they also determined absolute injury rates for pedestrian falls per distance walked for both the summer months (April to October) and the winter months (November to March). They also calculated the absolute injury rate for pedestrian falls in winter not occurring on snowy/icy surfaces but stated that the distance walked 'cannot be partitioned by surface condition' [p. 364]. They calculated increased relative injury rates for winter months compared to summer months of 2.35 for women and 1.94 for men. Using the absolute injury rates given by Elvik & Bjørnskau (2019), the relative injury rates for pedestrian falls in winter not occurring on snowy/icy surfaces, at 0.67 for women and 0.63 for men, result in a lower risk for pedestrian falls than in summer. The authors suspected possible behavioural adaptations in the winter months as the reason. However, Elvik & Bjørnskau (2019) did not provide absolute or relative injury rates for pedestrian falls in winter occurring on snowy/icy surfaces but conclude from the remaining indicators that snowy/icy surfaces make a 'huge contribution' to the calculated risk in winter.

In addition, several other studies were found that looked at the risk of pedestrian falls in winter or on snowy/icy surfaces but did not consider distance walked as exposure:

Furian et al. (2011) analysed a survey among Austrian inpatients or outpatients after a home, leisure or sports accident and found that 47.9% of all pedestrian accidents without vehicle involvement occurred in the three months December to March, which results in a risk ratio for the winter months of 1.9. In addition, 45.1% of these patients mentioned snowy/icy surfaces as the relevant cause of their single pedestrian accident.

Based on injury records from three hospitals in Gothenburg, Linköping and Umeå (Sweden), Öberg et al. (1996) calculated injury rates due to pedestrian falls in relation to population size. They determined risk ratios for falls on snowy/icy surfaces of 7.3 compared to bare surfaces in summer and of 3.3 compared to bare surfaces in winter. Presumably, they did not consider temporal exposure to such conditions.

Further studies have been found on fall frequencies among elderly people in winter vs summer months, that did not consider distance travelled (Jacobsen et al., 1995; Pajala et al., 2008; Duckham et al., 2013; Gyllencreutz et al., 2015). However, exposure to periods of snow or ice seems to be particularly relevant for older people, as the literature shows that they are more likely to refrain from leisure activities in such weather than from mandatory activities (Öberg et al., 1996; Baier et al., 2009; Cools et al., 2010; Böcker et al., 2013; Termida et al., 2018).

2.4 Severity of falls

Berntman (2003) analysed the consequences of single pedestrian accidents on the basis of official statistics and a hospital study in five Swedish cities. The author concludes that single pedestrian accidents on snow/ice sometimes have more severe consequences than on dry or wet surfaces. It should be noted that her data set only includes single pedestrian accidents that resulted in some form of medical treatment (or death).

3 Data and methods

3.1 Overview

Figure 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 pedestrian falls in snowy/icy as well as in other weather conditions. Pedestrian exposure was obtained from the recurring German HTS 'Mobility in cities – SrV' (Ahrens et al., 2014) and validated against results from an online survey and manual counts carried out as part of this study. Meteorological data were used to assign snowy/icy and other weather conditions to pedestrian exposure and to account for the substantial differences in the number of days for these two conditions (Wetterdienst, 2018). In the online and on-site surveys carried out as part of this study, the questions about falls and traffic behaviour 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 Figure 1. Further details on the data used in this study are provided in Bärwolff et al. (2022).

In this study, the absolute risk was defined as the number of falls per distance walked. The risk in snowy/icy conditions e.g. was calculated by dividing (*1*) the mean number of falls in snowy/icy conditions per person during the study period (obtained from field and online surveys carried out as part of this study) by (*2*) the mean distance walked in snowy/icy conditions per person (obtained from the HTS) and (*3*) the number of days with snow/ice in the study period (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 walked from the HTS. The relative risk of falling in snowy/icy conditions compared to other weather conditions was calculated by dividing the numbers of falls per distance walked in snowy/icy conditions by the number of falls per distance walked in other conditions. Confidence Intervals (CI, 95%) were calculated for mean values of pedestrian falls and distances walked. 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 pedestrian falls were surveyed.

All data on the statistical significance of the results obtained with this study refer to the 5% level ($p < 0.05$).

3.2 Self-reported falls from retrospective surveys

Retrospective field surveys among pedestrians 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 on major roads and access roads, at crossing facilities and at PT stops on working days excluding school breaks and public 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. Persons who did not wish to take part in the survey were also counted. Overall, 46% of the persons approached took part in the survey. This proportion was similar for the surveys in times of snowy/icy weather and in times of other weather.

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 Federal 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 pedestrian falls on public roads, paths, and sidewalks in the 5-year period before the survey in both snowy/icy and other conditions.

We have chosen a period of 5 years because, similar to road traffic accidents, falls are rather rare events. There is a high probability that a person has not experienced any fall within the last one or two years. In order to achieve the most accurate results possible for such rare events and a sufficient number of cases at the same time, either the sample of respondents can be significantly increased, or the analysis period can be extended. Due to limited financial resources, we decided to do the latter.

The disadvantage of a long analysis period of 5 years is that the further an event is in the past, the more the memory fades. Especially among older respondents or in the case of falls without significant consequences, the memory may fade rather sooner than later (Ganz et al., 2005). Basically, this might mean that the number of falls reported by the respondents tends to be too low and that more recent falls are reported more reliably than earlier ones. We have not found any empirical evidence in the literature about the specific pattern of this underreporting. For this study, we therefore assume that falls in snowy/icy conditions and other weather conditions are remembered and reported to a similar extent, and that the time period of 5 years is suitable for asking for the occurrence of falls.

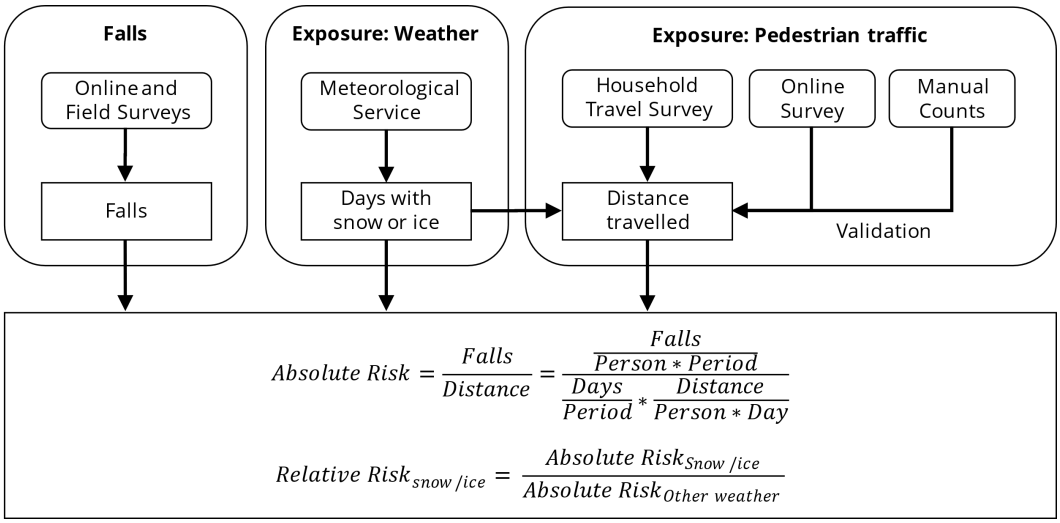

Figure 1 Research approach: Data sources and formulas for computing absolute and relative risks for pedestrian falls.

Among the 2 104 persons interviewed in the field, 2 090 could remember the number of falls as pedestrians in the 5-year period before the survey. They reported a total of 710 pedestrian falls. Among the 3 338 online respondents, 3 208 people could remember the number of falls as pedestrians in this period. They reported a total of 4 472 pedestrian falls. In total, 5 298 participants reported 5 182 pedestrian 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 stated that they had not experienced any falls in the five-year period, the sample size for detailed information about the respective last fall is reduced compared to previous questions. In the field surveys, 294 respondents gave information on their last pedestrian fall in snowy/icy conditions and 67 respondents gave information on their last pedestrian fall in other conditions. Online, 677 respondents gave information on their last pedestrian fall in snowy/icy conditions and 185 respondents gave information on their last pedestrian fall in other conditions.

3.3 Weather data

Weather data were obtained from the official German Weather Service DWD (Wetterdienst, 2018). The weather station nearest to the place of residence of the respondents to the HTS 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 Figure 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 snowy/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, showing that it should be considered in as much detail as possible.

3.4 Pedestrian travel behaviour

The changes in pedestrian travel behaviour on snowy/icy days were quantified based on the following data sources:

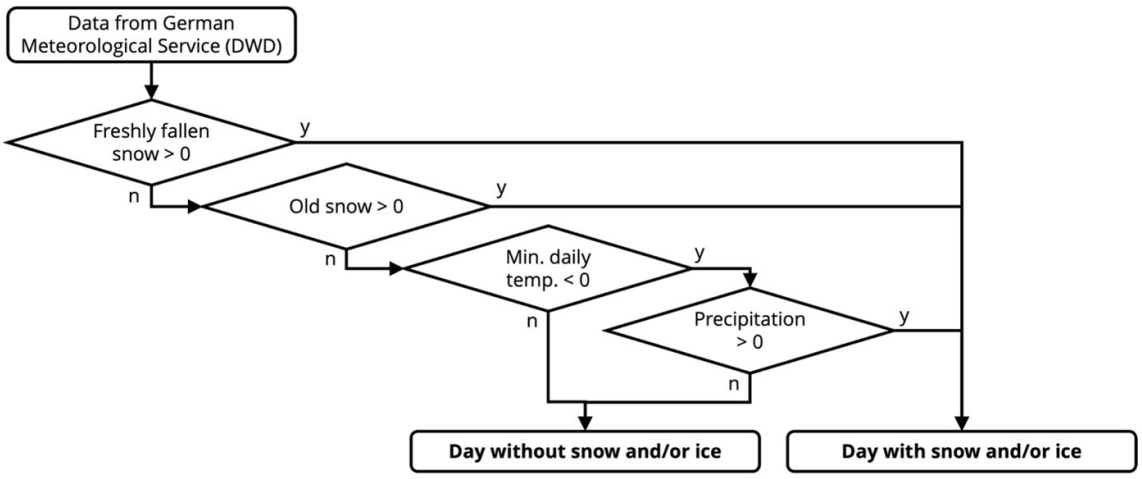

Figure 2 Scheme to assign a day to have snowy/icy or other weather conditions using meteorological data.

- raw data from 22 772 respondents in the German HTS 'Mobility in Cities – SrV' (Ahrens et al., 2014),
- responses on usual travel behaviour 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, and
- short term pedestrian counts from video recordings from this study at 13 sites on both snowy/icy days and other days.

3.5 Travel behaviour

3.5.1 Household Travel Survey (HTS)

Data from the HTS 'Mobility in Cities – SrV' from 2013 (Ahrens et al., 2014) was analysed 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 their trips and further information on person and household characteristics for one diary day including only working days, while school and public 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). The HTS data were used to estimate the average number of trips per person on the diary day and the average distances walked. The distances walked were obtained (*1*) for pure pedestrian trips and (*2*) for all pedestrian stages (pure pedestrian trips plus pedestrian stages within public transport [PT] and motorized individual transport [MIT] trips). As this HTS records the distances travelled for trips, but not for stages, constant distances were applied for inbound and outbound stages. According to Brög (2017), for pedestrian stages within MIT trips a walking distance of 0.1 km and for pedestrian stages within PT trips a walking distance of 0.6 km were applied. The distances walked were also used as the denominator for calculating absolute and relative risks.

3.5.2 Online survey

The online survey included questions about respondents' travel behaviour 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 the frequency of exclusively pedestrian trips (without pedestrian stages to/from other means of transport) in typical pleasant summer weather conditions 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). For snowy/icy weather conditions, respondents were asked whether pedestrian trips were made 'more often', 'as always', 'less often' or 'never' compared to typical pleasant summer weather. Respondents were also asked about the reasons for changes in behaviour (if they stated

any).

3.5.3 Manual counts

Video recordings were carried out parallel to the field surveys. Video cameras were installed along 13 street sections within seven study areas observing sidewalks in public space. All study areas are located in Germany around 50 and 51 degrees of latitude. The study areas in western Germany are located near the Dutch border in the maritime climate zone:

- The city of Aachen has 250 000 inhabitants, lies at an altitude of approximately 175 meters and minimum temperatures below 0 degrees Celsius usually only occur on a few days per year.
- The town of Roetgen has approximately 8 700 inhabitants, lies at an altitude of approximately 410 meters and daily minimum temperatures below 0 degrees occur there in a few weeks per year.

In contrast, the study areas in eastern Germany near the Czech border are located in the transitional climate zone:

- The city of Dresden has approximately 570 000 inhabitants and is located at an altitude of approximately 110 meters. There, daily minimum temperatures below 0 degrees Celsius usually occur in one to two months per year.
- The town of Altenberg has approximately 7 900 inhabitants, is situated at an altitude of approximately 750 meters and has daily minimum temperatures below 0 degrees Celsius for two to four months per year.

In most of the study areas, several sections (named A, B, C, …) were observed along the streets. Video data for all street sections were collected for snowy/icy and other weather conditions in the years 2015 to 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 public holidays. Similar weekdays and time periods were chosen for snowy/icy and the other weather conditions to ensure comparability. At each section, pedestrians were counted from the video footage for at least 45 minutes. In sections with low pedestrian traffic, up to 345 minutes were counted to generate a meaningful sample. Further videos were recorded at different sections, but these are not included because less than 50 pedestrians were counted in the six hours of total video on days with other weather conditions than snowy/icy. In total 5 286 pedestrians were counted in the 13 sections.

4 Results

4.1 Distances walked

4.1.1 Household Travel Survey (HTS)

Figure 4 gives an overview of distances walked by HTS respondents by age, gender, and weather conditions calculated with two different methods (trips only and including stages). The distance walked among all respondents (regardless of the weather conditions on diary day) is about 0.78 km per person and day (95% CI [0.76, 0.80]) for exclusively pedestrian trips and about 1.10 (95% CI [1.07, 1.12]) when also pedestrian stages of PT and MIT trips are considered. Those values do not differ statistically significant on reporting days with weather conditions other than snowy/icy. On reporting days with snowy/icy conditions, they increase to 0.85 km of exclusively pedestrian trips per person and day (95% CI [0.79, 0.91]) when only exclusively pedestrian trips are considered, an increase of 10% which is slightly not statistically significant. When also pedestrian stages of PT and MIT trips are considered, the distance walked increases to 1.14 km (95% CI [1.14, 1.27]) in snowy/icy conditions by a statistically significant 11%. Statistically significant increases in the distance walked per person and day in snowy/icy compared to other conditions are otherwise only observed among men (from 0.99 to 1.12) and among those aged 18–44 (from 1.08 to 1.27), and only when pedestrian stages during PT and MIT trips are considered.

Among all respondents we found that woman reported a statistically significant higher overall walking distance than men. We also found, that middle-aged respondents (45–64) reported a statistically significant lower overall walking distance, while respondents older than 65 reported a statistically significant higher overall walking distance compared to the other age groups. Those differences are statistically significant for both calculation methods (trips only as well as stages included). The difference between respondents aged 0–17 and those aged 45–64 is only statistically significant when stages of PT and MIT trips are included, as they account for a higher proportion of the distance walked

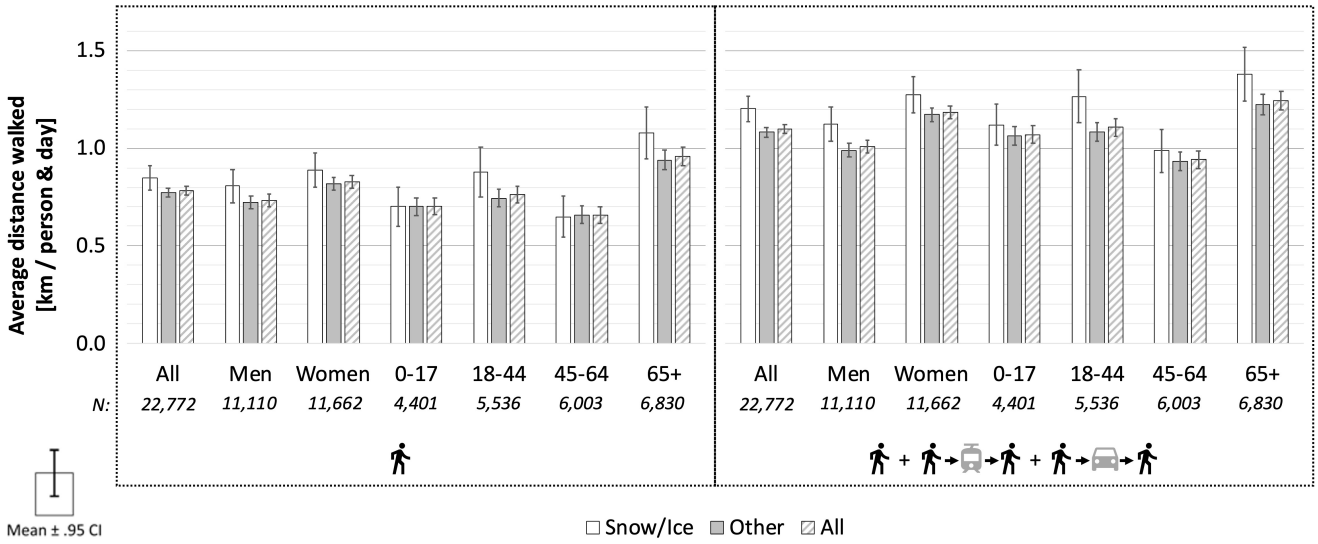

Figure 4 Average daily walking distances covered by HTS respondents in various weather conditions, by gender, age and calculation method (left: pedestrian trips only, right: including pedestrian stages of PT and MIT trips)

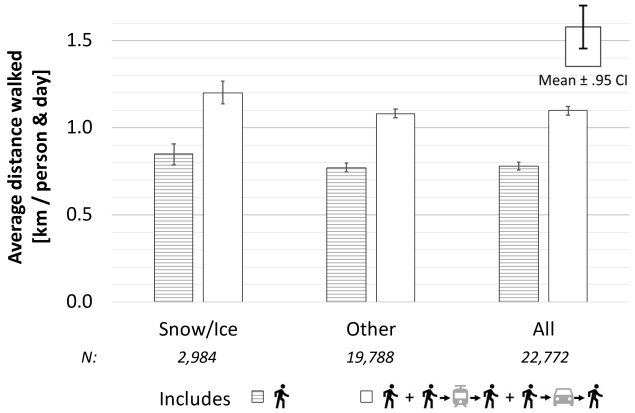

Figure 3 Average daily walking distances covered by HTS respondents in various weather conditions, by calculation method (left: pedestrian trips only, right: including pedestrian stages of PT and MIT trips)

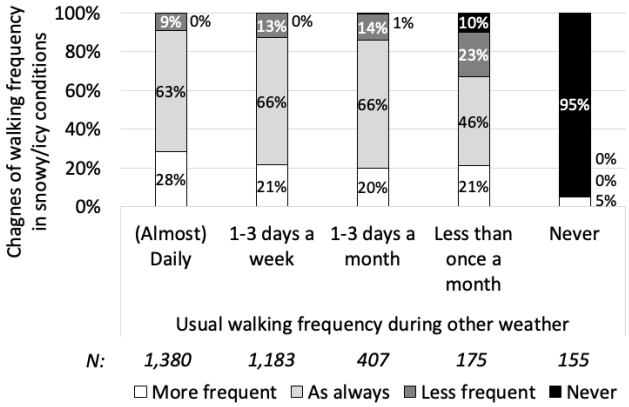

Figure 5 Modification of walking frequency in snowy/icy conditions compared to other weather (n.a. = not answered)

by younger respondents (see Figure 4)

4.1.2 Validation with other data sources

The analysis of the online survey shows that of those who in other weather travel entire trips as a pedestrian at least once a month, 24% increase and 11% decrease this frequency in snowy/icy conditions. Of those stated to who travel entire trips as a pedestrian less than once a month, 21% increase and 33% decrease this frequency in snowy/icy conditions. Of those who reported never completing entire trips as a pedestrian in other weather conditions, 5% reported doing so in snowy/icy conditions. See Figure 5 for a detailed view of the answers.

Among those respondents who reported an increased walking frequency in snowy/icy conditions, 68% stated an increased risk of road accidents with other modes of transport as a reason, while 53% stated poor winter maintenance on facilities of other modes of transport as a reason. In contrast to that, 31% of the respondents stated slower travel speeds of the other modes of transport as a reason and 19% stated loss of comfort of the other modes of transport. While these are all push factors from other modes of transport, 15% named a pull factor: more recreational walking.

Among those respondents who reported a decreased walking frequency in snowy/icy conditions, 64% stated an increased risk of falls as a reason, while only 8% mentioned the increased risk of collision with other road users. In addition to that, more than half of the

respondents (53%) stated poor winter maintenance as a reason. Slower walking speeds (49%) and a loss of comfort (47%, e.g. due to cold) were also mentioned by almost half of the respondents who walk less in snow/ice. 25% said that they make fewer recreational trips as a pedestrian in snow/ice and 18% mentioned darkness as an impediment.

The reported reasons for modified walking frequency in snowy/icy conditions are shown in Figure 6.

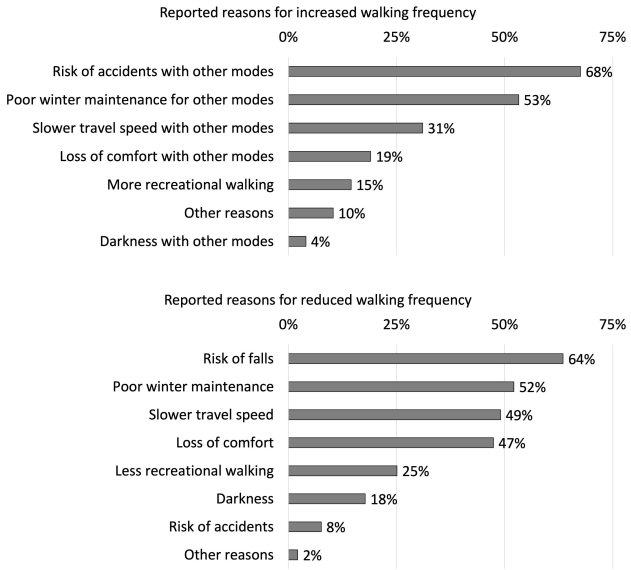

Figure 6 Reasons for increased (top) and reduced (bottom) walking frequency in snowy/icy conditions reported in the online survey.

The manual video-based counts show mixed results. In Dresden we notice decreases of up to 36% (Bergstraße) as well as increases of up to 160% in pedestrian volume in snowy/icy conditions. In the two areas in Aachen, we find slight decreases of 4% to 8%, quite similar to the area in Roetgen. In Altenberg Rathausstraße, we find increases of pedestrian volumes of 20% to 69%. Across all sections, we find an average increase in pedestrian traffic of 28% (95% CI [14%, 42%]). Overall, the increase in snowy/icy conditions is significantly greater among male pedestrians than female pedestrians. Regarding different age groups, we observe a stronger increase among middle-aged people (30–64) compared to younger people (15–29), while we even observe a decline in pedestrian volume among older people (65+). The results of the manual counts are shown in Table 2.

4.2 Risk of falls

4.2.1 Absolute risk

The absolute risk of falls per distance walked varied significantly depending on the survey type and timing. During online surveys conducted in times of snow/ice, the overall risk of falls per 10 000 kilometers walked was calculated at 9.76 (95% CI [9.25, 10.27]) based on 'trips' and at 6.95 (95% CI [6.61, 7.29]) based on 'stages'. Based on the field survey in times of snow/ice, the values of 4.11 (95% CI [3.44, 4.78]) based on 'trips' and 2.93 (95% CI [2.45, 3.40]) based on 'stages' are 58% lower compared to the field survey in times of other weather. Based on the field survey in times of other weather, there are values of 1.47 (95% CI [1.16, 1.78]) based on 'trips' and 1.05 (95% CI [0.83, 1.27]) based on 'stages', which in turn are 64% lower than the field survey in times of snow/ice. Also, all of the values obtained for falls per distance walked based on the 'stages' method are 29% lower than those based on the 'trips' method, as the distance walked includes more kilometers. Figure 7 shows the differences in overall risk of falls per distance walked by survey type and timing as well as exposure calculation method.

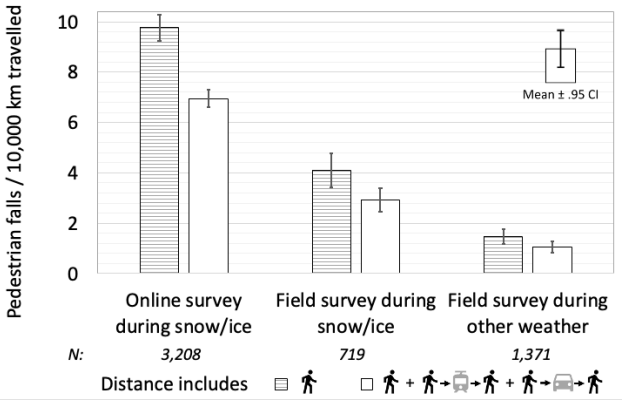

Figure 7 Falls per 10 000 km walked by survey method and method of calculating distances from HTS (pedestrian trips only vs pedestrian trips and pedestrian stages of PT and MIT trips

In all three surveys, regardless of the age and gender of the respondents and regardless of the method used to calculate the exposure, the risk of falling per distance travelled is several times higher in snowy/icy than in other weather conditions. These differences are of high statistical significance. For example, from the field survey in times of different weather, using stages for exposure calculation, the risk of falls per 10 000 kilometers walked is 7.76 (95% CI [6.09, 9.43]) in

Table 2 Results of manual pedestrian counts in different weather conditions by city, area, and section

City	Area	Section	Duration [min]	Other weather (counts)	Snow/Ice (counts)	Delta
Aachen	Lothringer Straße	A	90	105	100	-5%
		B	90	164	151	-8%
	Vaalser Straße	A	45	56	54	-4%
Altenberg	Rathausstraße	A	240	209	354	+69%
		B	345	370	499	+35%
		C	285	94	113	+20%
Dresden	Bergstraße	A	150	169	218	+29%
		B	180	294	189	-36%
	Liebigstraße	A	75	93	190	+104%
		B	75	137	356	+160%
	Zellescher Weg	A	75	406	306	-25%
		B	90	255	294	+15%
Roetgen	Bundesstraße	A	195	53	57	+8%

snowy/icy compared to 0.24 (95% CI [0.15, 0.33]) in other weather conditions. Those differences are statistically significant. More detailed results on the difference in risk of falls between snowy/icy and other conditions will follow in the next section.

While there are no statistically significant differences between women and men in any of the absolute risk of falls, there are a few between the age groups. Using the 'stages' method for exposure calculation, in both the online survey and the field survey in times of snow/ice, respondents aged 65 and older have a statistically significant lower risk of falls per distance walked in snowy/icy conditions compared to younger respondents aged 18–44. The same trend is seen in responses to the field survey in other weather conditions, but here the differences are not statistically significant. In contrast, using the 'stages' method, these differences are also statistically significant for the field survey in times of snow/ice. Furthermore, with the 'stages' method, the falls per distance walked in snowy/icy conditions of the respondents aged 65 and older is also statistically significant below the value of those aged 18 to 44 in both the online and the field surveys conducted in times of snow/ice. Regarding falls per distance walked in other weather conditions, there are no statistically significant differences between the age groups.

Figure 8 shows the number of falls per distance walked in different weather conditions by survey type and timing, gender, and age using the 'stages' method for exposure calculation.

4.2.2 Relative risk

The results of all three surveys show a significantly higher average risk of falls for pedestrians in snowy/icy than in other weather conditions. While there are statistically significant differences in the absolute risk of falls per distance depending on survey type and timing, there are no such statistically significant differences for the relative risk of falls in snowy/icy in relation to other weather conditions. Based on the 'stages' method for exposure calculation, the relative risk of falls is 53 (95% CI [46, 59]) based on the online survey in times of snow/ice, 54 (95% CI [28, 80]) based on the field survey in times of snow/ice and 33 (95% CI [18, 47]) based on the field survey in times of other weather. There is a tendency towards lower relative risk of falls with increasing age of the respondents, but these are not statistically significant in most cases. Only the online survey in times of snow/ice shows a statistically significant lower relative risk of falling in snowy/icy in relation to other weather conditions for respondents aged 65 and older compared to respondents aged 18 to 44. The calculated relative risks of falling are shown in Table 3.

4.2.3 Severity and reporting

Regarding the severity of falls, there are no statistically significant differences between falls in snowy/icy and other conditions in the responses of respondents to the two field surveys. In the online survey in times of snow/ice, the respondents indicated less frequent

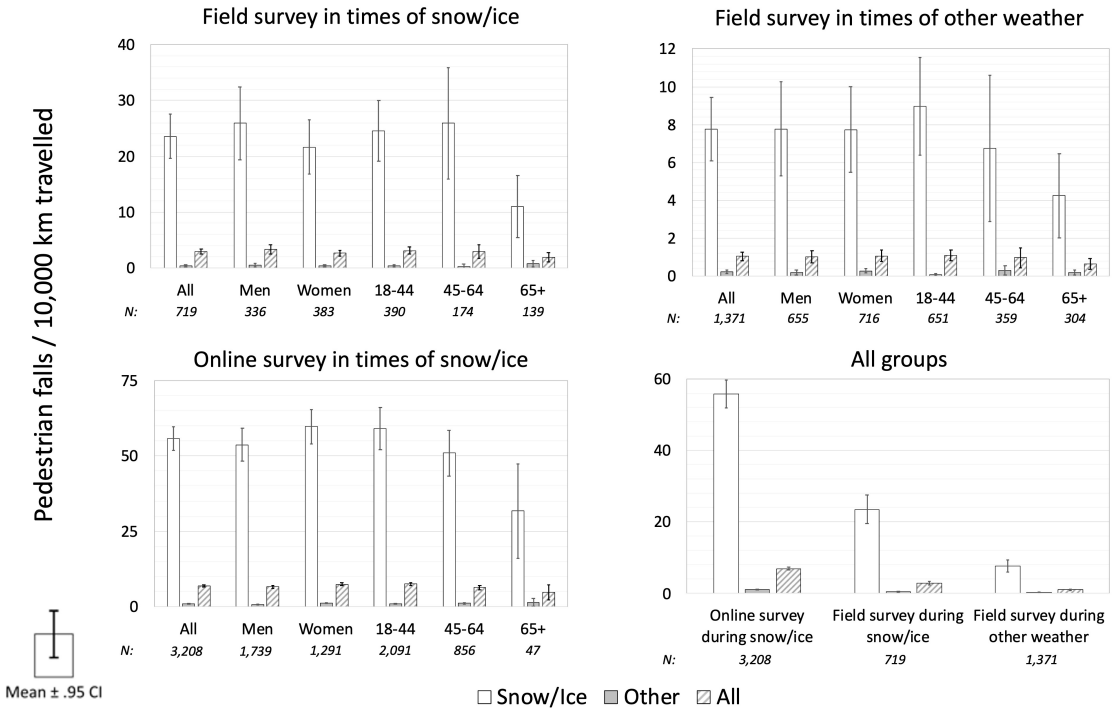

Figure 8 Falls per 10 000 km walked in different weather conditions by survey method, gender, and age, walking distances based on exclusively pedestrian trips as well as pedestrian stages of PT and MIT trips; Top left: Field survey conducted in times of snow/ice; Top right: Field survey conducted during other weather; Bottom left: Online survey conducted in times of snow/ice; Bottom right: All groups compared for the three surveys

Table 3 Relative risks for pedestrian falls in snowy/icy conditions in relation to other conditions by survey method, age, and gender with 95% CI

	Field surveys		Online survey
	in times of other weather	in times of snow/ice	in times of snow/ice
All	33 (95% CI [18, 47])	54 (95% CI [28, 80])	53 (95% CI [46, 59])
Men	44 (95% CI [09, 78])	52 (95% CI [13, 92])	65 (95% CI [52, 78])
Women	27 (95% CI [13, 42])	55 (95% CI [21, 89])	48 (95% CI [40, 56])
18–44	104 (95% CI [33, 175])	68 (95% CI [25, 112])	60 (95% CI [49, 71])
45–64	22 (95% CI [0, 44])	87 (95% CI [0, 222])	43 (95% CI [32, 54])
65+	22 (95% CI [3, 40])	13.4 (95% CI [2, 25])	21.5 (95% CI [0, 44])

hospitalization (1% vs 6%) and generally less frequent medical treatment (9% vs 28%) for falls in snowy/icy compared to other conditions (see Figure 9). Overall, there are almost no statistically significant differences between the surveys. However, for falls in snowy/icy conditions, hospitalization was reported less frequently in the online survey (1%) compared to the field surveys (8% and 7% respectively).

Considering data from all three surveys, within the age groups no statistically significant differences were found in the medical treatment of falls in snowy/icy compared to other conditions. However, there were

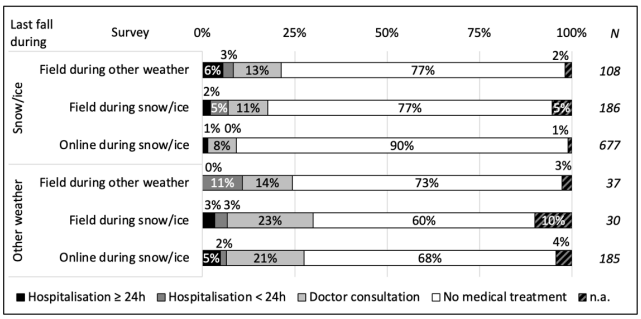

Figure 9 Intensity of medical treatment after respondents' last fall by weather and survey method (n.a. = not answered).

differences between the age groups: After a fall in snowy/icy conditions, respondents aged 18–44 needed medical treatment statistically significant less often (7%) than those over 45 (25%). The results also show that only 2% of falls among young adults (18–44) in snowy/icy conditions resulted in hospitalization, while this proportion is 5% among middle-aged respondents (45–64) and 21% among the elderly (65+; all differences statistically significant). A similar trend can also be seen for falls in other weather conditions, but due to the smaller sample size there is only one statistically significant difference: the proportion of medically treated falls is higher among the elderly (65+) at 41% than among those aged 18 to 64 at 17% (see Figure 10).

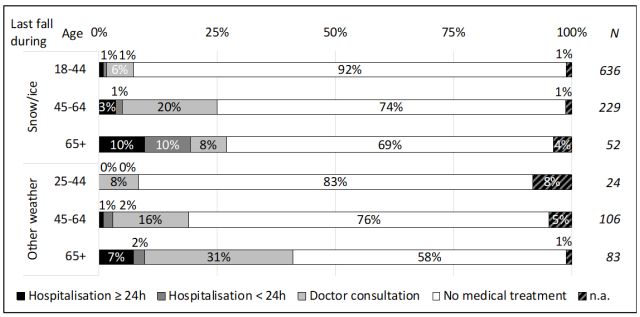

Figure 10 Intensity of medical treatment after respondents' last fall by weather conditions and age (n.a. = not answered)

91% of the respondents' most recent pedestrian falls in snowy/icy conditions were not reported to an insurer, while this level of underreporting is 76% for the most recent pedestrian falls during other weather conditions. Despite not being defined as a road traffic accident, a total of four people stated that they had reported their pedestrian case 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. However, this difference corresponds almost exactly to the difference in medical treatment already mentioned. In snowy/icy conditions, 13% of pedestrian falls requiring medical treatment were reported to insurers, compared to 12% in other weather conditions. On the other hand, none of the pedestrian falls without medical treatment were reported, regardless of the weather conditions.

5 Discussion

5.1 Distances walked

Existing studies show both increases and decreases of pedestrian volumes in winter weather. In these studies, mostly cross-sectional counts were carried out and a similar level of variation can be seen in the cross-sectional counts carried out manually as part of this study. Cross-sectional counts implicitly take travel distances into account, as longer trips are more likely to pass along a count cross-section than shorter trips. However, we did not find any studies that explicitly analysed walking distances in different weather conditions.

The analysis of pedestrian trips from an HTS from 13 larger German cities (Ahrens et al., 2014) shows no statistically significant differences in the average distance walked per person and day between snowy/icy and other days. Nevertheless, there is a predominant tendency towards a slight increase in distances walked, except for the age groups 0 to 17 and 45 to 64. The pedestrian trips mentioned only include trips for which no other means of transport were used.

When pedestrian stages of PT and MIT trips are also considered, there is a statistically significant increase in the average distance walked per person and day of 11% for snowy/icy reference days compared to days with other weather conditions. While this trend is evident for all genders and age groups using the 'stages' method, the increase is only statistically significant for men and the age group 18 to 44. This group also includes students who presumably transfer some trips more flexibly from bicycle to PT because most of them have a semester ticket. Overall, we suspect a shift in the modal split, with people switching from cycling to PT in snow/ice (including pedestrian stages to and from PT stops) as well as to pedestrian-only trips.

The HTS data show a trend towards a (non-significant) increase in distance travelled among older people, while our manual counts show a slight decrease in traffic volume among the elderly, which Baier et al. (2009) also found.

It should be noted that an increase in the average distance walked per person and day based on the HTS can result either from more frequent or longer pedestrian trips (or stages), or from an increase in both trip (or stage) frequency and distance. This means a change in the transport mode used can also affect

the average distance walked per person and day with a transport mode. However, behind increases in the average distance walked in snowy/icy conditions, we rather suspect increases in the number of pedestrian trips or stages, as we assume that on average no additional distances are walked in such conditions.

Whether all pedestrian stages are included has a decisive influence on the results of this study. The overall walking distances that additionally include the pedestrian stages of PT and MIT trips are 41% higher than those based only on exclusively pedestrian trips. Although in this study we chose a rather simple approach to include distances of these stages as constants, we assume that this still brings us much closer to reality. Koszowski et al. (2024) developed a more comprehensive methodology for modelling distances of pedestrian stages in trip based HTS, which could be used in future studies.

If pedestrian stages are considered (in contrast to whole pedestrian trips), there is a statistically significant increase in the overall average distance walked per person and day in snowy/icy conditions. From this it can be concluded that a certain number of cycling trips are transferred to MIT or PT trips, whose pedestrian stages in turn increase the average distance walked.

In general, the HTS provided a much smaller sample for the distances walked in snowy/icy conditions than for other weather conditions due to the distribution of the reporting days, which is why only some of the findings based on it are of statistical significance. However, there is an overall tendency that average distances walked per person and day range from unchanged to slightly increased in snowy/icy conditions.

The online survey conducted as part of this study shows that among people who walk at least monthly in other weather conditions, the majority maintain this frequency in snowy/icy conditions (64%), while 24% walk more often and 11% walk less often. Of those respondents who usually walk less than monthly, 21% indicated an increase and 33% a decrease for snowy/icy conditions. Therefore, it can be assumed that regular pedestrians tend to walk even more frequently in snowy/icy conditions, while irregular pedestrians tend to do the opposite.

In the online survey, the main reasons mentioned for increasing the frequency of walking in snow/ice were push factors, in particular the risk of accidents with other modes of transport and poor winter maintenance for other modes of transport. The main barriers stated to walking in snowy/icy conditions were the risk of falling as a pedestrian, poor winter maintenance of pedestrian facilities, slower walking speeds and a loss of comfort. However, a bias due to selection or social desirability cannot be ruled out with these statements, as the online survey was published under the title 'Traffic behaviour and risk of falls in snow and icy conditions'.

The results of the online survey show that subjective safety is a strong barrier to walking, especially for people who generally rarely walk in snowy/icy conditions. It seems to be these people who can be activated as pedestrians through improved winter maintenance.

Generally, the volume of pedestrian traffic is significantly less affected by snowy/icy conditions than the volume of cycling, as analysed by Bärwolff & Gerike (2023). This also confirms the findings of Bongiorno et al. (2019). In contrast, pedestrian traffic in part even slightly increases during snowy/icy conditions. We assume this is caused by a modal shift from cycling to PT including more pedestrian stages from and to the transit stops. According to our online survey, both cyclists and pedestrians have in common that perceived safety plays an important role in their mode choice in snowy/icy conditions. But respondents seem to be more concerned about their safety on cycling facilities compared to pedestrian facilities.

5.2 Risk of falls

The absolute risks for pedestrian falls determined in this study range between 1.1 and 9.8 falls per 10 000 km walked, depending on the survey type and timing as well as the exposure calculation method. Since all previous studies quantified injuries due to pedestrian falls, but not the number of falls themselves, our results on the absolute risk of falls are not directly comparable with the literature. However, for those pedestrian falls for which more detailed information was provided, the overall proportion of hospitalizations was 4%. If we assume this proportion for all reported falls in our study, then this results in 4.4 to 39.2 hospitalizations per million km walked depending on survey type and timing as well as exposure calculation method. The value of 4.4 hospitalizations per million km is above the values determined by Mindell et al. (2012), Oxley et al. (2018) and Aldred (2018), but below those determined by Elvik & Bjørnskau (2019). However, in Aldred (2018), initial questions were asked about

traffic accidents, which may have meant that not all pedestrian falls were reported, as respondents may not have categorized them as official accidents.

The overall risk of pedestrian falls differs significantly depending on the survey type and timing. Compared to the field survey conducted in times of other weather, it is more than twice as high based on the field survey conducted in times of snow/ice and more than five times as high based on the online survey conducted in times of snow/ice. We assume that respondents were best able to remember falls occurring in the weather conditions that prevailed at the time of the survey. We also suspect a bias by selection for the online survey in the sense that people suffering from falls were more likely to take part whilst the staff approached random people in the field survey.

Respondents were given the opportunity both online and in the field to indicate if they feel that they could not remember the exact number of falls they had in each weather condition reliably (which only a few did). However, it cannot be ruled out that some respondents could not remember the number over the past 5 years exactly and therefore only made a rough estimate. We assume that the resulting bias is similar for falls in all weather conditions and therefore results are still comparable. The results of Bärwolff & Gerike (2023) show similar differences between the survey types for the risk of cyclists falling: Here, too, the risk is almost twice as high in the field survey conducted in times of snow/ice compared to the field survey conducted in times of other weather conditions, and the risk in the online survey conducted in times of snow/ice is even higher. The above-mentioned survey effects can therefore be seen in falls involving both pedestrians and cyclists. We consider these difference to be an important methodological finding from this study which should be considered in future research, especially when only one of the survey types is applied. We believe that the results from the online survey in this study appear to be too high due to a sample bias towards persons who recently had a fall and consider the on-site survey to be more trustworthy.

The overall risk of pedestrian falls is 29% lower if not only exclusively pedestrian trips but also stages as part of PT and MIT trips are included in the exposure. This is the result of the higher average distance walked per person and day when including stages as part of PT and MIT trips. Since pedestrian falls can also occur on these stages, we consider their inclusion to be more accurate. However, as no dedicated distances were recorded for these stages in the HTS, we applied constant values per trip. More detailed recording of such stages in the HTS or more comprehensive methods for estimating the distances walked might increase the accuracy of the results in the future.

The risks for pedestrian falls in snowy/icy conditions determined in this study range between 7.8 and 79.0 falls per 10 000 km walked, depending on the survey type and timing as well as the exposure calculation method. Considering the proportion of hospitalizations of 3% due to pedestrian falls in snowy and icy conditions from the surveys, this results in 23.4 to 237 hospital admissions per million kilometers walked in snowy/icy conditions. The value of 23.4 hospital admissions per million kilometers is significantly higher than that of E Eriksson & Sörensen (2015), but in the upper range of the results of Elvik & Bjørnskau (2019) for winter months.

With respect to the potential survey effects and the comparison with the results from other studies (Mindell et al., 2012; Oxley et al., 2018; Aldred, 2018; Elvik & Bjørnskau, 2019), we conclude that the risk of falls from the field survey conducted in times of other weather including exposure from pedestrian stages of PT and MIT trips (which shows the lowest absolute risks) gives the best estimate.

The risk of falls per distance walked in snowy/icy conditions tends to be lower for respondents aged 65 and older compared to younger respondents, especially to those aged 18–44. This contrasts with the findings of Elvik & Bjørnskau (2019), who found increased risks among the elderly in winter months, especially among those aged 75 and older. We suspect that many people between 65 and 75 walk particularly carefully in snowy/icy conditions and that some of those who would feel unsafe due to their physical condition refrain from trips, which could lead to a reduced risk of falling per distance walked. The increased risk of injuries due to pedestrian falls, especially among those aged over 75 as determined by Elvik & Bjørnskau (2019), could be due to the assumption that careful walking in this age group no longer mitigates declining physical abilities. It should be noted that in our surveys only one third of the respondents in the age group 65+ is aged over 75. Moreover, Elvik & Bjørnskau (2019) analysed injuries while this study focuses on all falls reported by respondents. Combined with the significantly increased severity of falls in other conditions of the

elderly determined in this study, this could mean that they fall less often, but suffer more injuries.

We determined relative risks for pedestrian falls in snowy/icy compared to other conditions of 33 to 54 depending on the survey type and timing. This is significantly above the values stated by Elvik & Bjørnskau (2019) and Furian et al. (2011), while they did not explicitly determine the risk of falls for snowy/icy conditions, but for the winter months. In their study, Elvik & Bjørnskau (2019) also state values for 'winter with walking surface as summer', where the risk is even lower than in summer. This shows that the risk of falling in snowy/icy compared to other conditions in the data from Elvik & Bjørnskau (2019) would probably be significantly higher than the risk for winter compared to summer months and thus closer to the results of our study.

We found a nonsignificant tendency towards a lower relative risk of falls in snowy/icy compared to other conditions with increasing age of the respondents. Elvik & Bjørnskau (2019) also state this tendency among women, while they cannot recognize a clear trend among men.

For each respondent's last reported pedestrian fall, we asked for more detailed information on medical treatment and reporting. Overall, the proportion of falls causing medical treatment is around 20 to 25% and the proportion of falls causing hospitalization is around 10%. In contrast to the risks per distance walked, there are hardly any significant differences in the severity of the falls between those in snowy/icy and those in other conditions. There are also hardly any significant differences according to survey type and timing.

At first glance, this contradicts the findings of Berntman (2003), who recorded more severe consequences in the case of falls on snow/ice. However, the data sets used in Berntman (2003) are hardly comparable with the responses to our surveys: In terms of the severity of falls, we primarily refer to the proportion of medical treatment in all falls, whereby a large proportion of the falls reported to us did not result in medical treatment. In contrast, Berntman (2003) data set only contains falls or single pedestrian accidents that resulted in medical treatment, due to the method used.

There is a clear tendency for the probability of medical treatment and, in particular, hospitalization after pedestrian falls to increase with age. This tendency is significant for falls in snowy/icy conditions, but, due to the sample size, not for falls in other conditions.

Pedestrian accidents are generally not defined as road accidents and are therefore not systematically recorded by the police. The number of unreported cases is also high among insurers: almost exclusively falls causing medical treatment were reported. Since falls without medical treatment are not necessarily falls without injuries and long-term consequences, a lower number of unreported cases would be desirable. This is especially important for environmentally friendly modes of transportation like walking, which are promoted throughout the whole year to tackle climate change. Besides a broader definition of road traffic accidents, permanent recurring hospital studies could be a good alternative to increase transparency regarding the extent of pedestrian and cyclist falls in general and in snowy/icy conditions in particular.

The most important results of this study can be summarized as follows: The risk of falls per distance walked increases significantly in snowy/icy conditions, while the distance walked also tends to increase (or does not decrease significantly) and the injury severity does not differ significantly. Falls in snowy/icy conditions are therefore a serious risk and should be prevented by improved winter maintenance and campaigns to wear suitable footwear. At the same time, snow and icy conditions are becoming rarer in Germany, which is why these countermeasures are receiving less and less attention.

6 Conclusions

- Depending on the data source, we found stable or slightly increased pedestrian volumes in snowy/icy conditions.
- The risk of falls per distance walked increases significantly in snowy/icy conditions.
- The probability of medical treatment due to pedestrian falls does not change significantly in snowy/icy conditions.
- The risk of falls per distance walked in snowy/icy conditions tends to be lower for respondents aged 65 and older, but the general probability of hospitalization after falls increases with age.
- The risk of falling per distance travelled differs greatly depending on survey type (online vs field) and timing (during snow/ice vs during other weather).

- Including pedestrian stages of PT and MIT trips significantly influences study results and we assume leads to more realistic results.
- While pedestrian falls are not recorded by the police, only those that cause medical treatment are reported to insurers.
- The findings underline the importance of winter maintenance on pedestrian facilities to promote walking throughout the whole year.

CRediT contribution statement

Martin Bärwolff: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing—original draft, Writing—review & editing. **Regine Gerike:** Conceptualization, Project administration, Resources, Supervision, Writing—review & editing.

Declaration of competing interests

The authors report no competing interests.

Funding

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

Acknowledgements

A presentation based on the same data, but with a different analysis method, was given at the International Conference on Theories and Concepts in Traffic safety (ICTCT) 2019 in Warsaw. In the subsequent proceedings in the Journal of Transactions on Transportation Sciences, an article was published dealing with the correlates of pedestrian and cyclist falls and pedestrians' and cyclists' behaviour in snowy/icy conditions as well as opinions on winter maintenance on sidewalks and cycle paths (Bärwolff et al., 2022). Research findings on cyclists' travel distances and risk of falls in snowy and icy conditions based on the same data and methodology as in this article were published in the Journal of Safety Research (Bärwolff & Gerike, 2023). The research findings on pedestrians' travel distances and risk of falls in snowy and icy conditions presented in this article are published for the first time.

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. We also like to thank Josephine Elvira Haagen for proofreading.

Ethics statement

No personal data was collected or processed for this study. In addition, no medical doctors were involved in this study and no experiments were conducted on and with humans or with human or embryonic cells. For these reasons, according to §1 (3) of the statutes of the Ethics Committee of TU Dresden, no consultation or approval by the Ethics Committee is required.

Availability of data

Data is available upon request.

References

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

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

Aldred, R. (2018), 'Inequalities in self-report road injury risk in Britain: A new analysis of National Travel Survey data, focusing on pedestrian injuries', *Journal of Transport & Health*, 9, 96–104, https://doi.org/10.1016/j.jth.2018.03.006.

Aultman-Hall, L., D. Lane, R. R. Lambert (2009), 'Assessing Impact of Weather and Season on Pedestrian Traffic Volumes', *Transportation Research Record: Journal of the Transportation Research Board*, 2140(1), 35–43, https://doi.org/10.3141/2140-04.

Baier, R., K. Schäfer, A. Klemps-Kohnen (2009), 'Verbesserung der Verkehrssicherheit älterer Verkehrsteilnehmer', Unfallforschung der Versicherer, https://www.udv.de/resource/blob/74640/6737406577425b5380c5e131fce16ff1/18-verbesserung-der-verkehrssicherheit-aelterer-vt-data.pdf.

Bärwolff, M., R. Gerike (2023), 'Cyclist's travel distances and risk of falls in snowy and icy conditions in German cities', *Journal of Safety Research*, 87, 64–75, https://doi.org/10.1016/j.jsr.2023.09.005.

Bärwolff, M., A. Reinartz, R. Gerike (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.

Berntman, M. (2003), 'Consequences of Traffic Casualties in Relation to Traffic-Engineering Factors - An Analysis

in Short-term and Long-term Perspectives', PhD thesis, Lund University, Lund, Sweden, Ph.D dissertation , https://lup.lub.lu.se/search/publication/2f34beda-2b1d-4beb-bce6-3e3042dd4e3a.

Böcker, L., M. Dijst, J. Prillwitz (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.

Bongiorno, C., D. Santucci, F. Kon, P. Santi, C. Ratti (2019), 'Comparing bicycling and pedestrian mobility: Patterns of non-motorized human mobility in Greater Boston', *Journal of Transport Geography*, 80, 102501–102501, https://doi.org/10.1016/j.jtrangeo.2019.102501.

Brög, W. (2017), 'Das hauptsächlich vernachlässigte Verkehrsmittel - Die Bedeutung des Fußverkehrs und die Nutzung des Straßenraums', Bundesweiter Umwelt- und Verkehrskongress, Wuppertal, http://www.umkehr-fuss-online-shop.de/kostenlose-downloads/category/43-plenum-freitag.html?download=303:plenum-broeg.

Bull, F. C., S. S. Al-Ansari, S. Biddle, K. Borodulin, M. P. Buman, G. Cardon, C. Carty, J. P. Chaput, S. Chastin, R. Chou, et al. (2020), 'World Health Organization 2020 guidelines on physical activity and sedentary behaviour', *British Journal of Sports Medicine*, 54(24), 1451–1462, https://doi.org/10.1136/bjsports-2020-102955.

Cools, M., E. Moons, L. Creemers, G. Wets (2010), 'Changes in Travel Behavior in Response to Weather Conditions: Do Type of Weather and Trip Purpose Matter? Transportation Research Record', *Transportation Research Record: Journal of the Transportation Research Board*, 2157(1), 22–28, https://doi.org/10.3141/2157-03.

Creemers, L., G. Wets, M. Cools (2015), 'Meteorological variation in daily travel behaviour: Evidence from revealed preference data from the Netherlands', *Theoretical and Applied Climatology*, 120, 183–194, https://doi.org/10.1007/s00704-014-1169-0.

Duckham, R. L., E. Procter-Gray, M. T. Hannan, S. G. Leveille, L. A. Lipsitz, W. Li (2013), 'Sex differences in circumstances and consequences of outdoor and indoor falls in older adults in the MOBILIZE Boston cohort study', *BMC Geriatrics*, 13(1), 133–133, https://doi.org/10.1186/1471-2318-13-133.

Eilert-Petersson, E., L. Schelp (1998), 'An epidemiological study of non-fatal pedestrian injuries', *Safety Science*, 29(2), 14–23, https://doi.org/10.1016/S0925-7535(98)00014-9.

Elvik, R., T. Bjørnskau (2019), 'Risk of pedestrian falls in Oslo, Norway: Relation to age, gender and walking surface condition', *Journal of Transport & Health*, 12, 359–370, https://doi.org/10.1016/j.jth.2018.12.006.

Eriksson, J., G. Sörensen (2015), 'Vintervädrets betydelse för att fotgängare skadas i singelolyckor', vti, https://vti.diva-portal.org/smash/record.jsf?pid=diva2%3A840682&dswid=7549.

ERSO (2023), 'Annual statistical report on road safety in the EU, 2022', European Road Safety Observatory.

Feleke, R., S. Scholes, M. Wardlaw, J. S. Mindell (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), https://doi.org/10.2307/2983630.

Furian, G., A. Kühnelt-Leddhin, R. Bauer (2011), 'Das Unfallrisiko auf Fußwegen in Österreich', Abschlussbericht zum Forschungsprojekt des Österreichischen Verkehrssicherheitsfonds, Bundesministerium für Verkehr.

Ganz, D. A., T. Higashi, L. Z. Rubenstein (2005), 'Monitoring Falls in Cohort Studies of Community-Dwelling Older People: Effect of the Recall Interval', *Journal of the American Geriatrics Society*, 53(12), 2190–2194, https://doi.org/10.1111/j.1532-5415.2005.00509.x.

Gao, J., C. B. M. Kamphuis, M. Dijst, M. Helbich (2018), 'The role of the natural and built environment in cycling duration in the Netherlands', *International Journal of Behavioral Nutrition and Physical Activity*, 15, 82–82, https://doi.org/10.1186/s12966-018-0715-z.

Gascon, M., T. Götschi, A. De Nazelle, E. Gracia, A. Ambròs, S. Márquez, O. Marquet, I. Avila-Palencia, C. Brand, F. Iacorossi, E. Raser, M. Gaupp-Berghausen, E. Dons, M. Laeremans, S. Kahlmeier, J. Sánchez, R. Gerike, E. Anaya-Boig, L. I. Panis, M. Nieuwenhuijsen (2019), 'Correlates of Walking for Travel in Seven European Cities: The PASTA Project', *Environmental Health Perspectives*, 127(9), https://doi.org/10.1289/EHP4603.

Gyllencreutz, L., J. Björnstig, E. Rolfsman, B. Saveman (2015), 'Outdoor pedestrian fall-related injuries among Swedish senior citizens - injuries and preventive strategies', *Scandinavian Journal of Caring Sciences*, 29(2), 225–233, https://doi.org/10.1111/scs.12153.

Hong, J. (2016), 'How does the seasonality influence utilitarian walking behaviour in different urbanization settings in Scotland?', *Social Science & Medicine*, 162, 143–150, https://doi.org/10.1016/j.socscimed.2016.06.024.

Jacobsen, S. J., D. J. Sargent, E. J. Atkinson, W. M. O'fallon, L. J. Melton (1995), 'Population-based Study of the Contribution of Weather to Hip Fracture Seasonality', *American Journal of Epidemiology*, 141(1), 79–83, https://doi.org/10.1093/oxfordjournals.aje.a117348.

Koszowski, C., R. Gerike, S. Hubrich, T. Götschi, M. Pohle, R. Wittwer (2019), 'Active Mobility: Bringing Together Transport Planning, Urban Planning, and Public Health', *Towards user-centric transport in Europe*, Springer International Publishing, , pp. 149–171, https://doi.org/10.1007/978-3-319-99756-8_11.

Koszowski, C., S. Hubrich, R. Wittwer, R. Gerike (2024), 'From Trips to Stages: A Methodology for Generating Stage Information in Trip-Based Household Travel Surveys', Manuscript submitted for publication.

Liu, C., Y. O. Susilo, A. Karlström (2015), 'Investigating the impacts of weather variability on individual's daily activity-travel patterns: A comparison between commuters and non-commuters in Sweden', *Transportation Research Part A: Policy and Practice*, 82, 47–64, https://doi.org/10.1016/j.tra.2015.09.005.

Liu, C., Y. O. Susilo, A. Karlström (2017), 'Weather variability and travel behaviour - what we know and what we do not know', *Transport Reviews*, 37(6), 715–741, https://doi.org/10.1080/01441647.2017.1293188.

Methorst, R., P. Schepers, N. Christie, M. Dijst, R. Risser, D. Sauter, B. Van Wee (2017), '"Pedestrian falls" as necessary addition to the current definition of traffic crashes for improved public health policies', *Journal of Transport & Health*, 6, 10–12, https://doi.org/10.1016/j.jth.2017.02.005.

Mindell, J. S., D. Leslie, M. Wardlaw (2012), 'Exposure-Based, "Like-for-Like" Assessment of Road Safety by Travel Mode Using Routine Health Data', *PLoS ONE*, 7(12), 50606–50606, https://doi.org/10.1371/journal.pone.0050606.

Miranda-Moreno, L. F., D. Fernandes (2011), 'Modeling of Pedestrian Activity at Signalized Intersections: Land Use, Urban Form, Weather, and Spatiotemporal Patterns', *Transportation Research Record: Journal of the Transportation Research Board*, 2264(1), 74–82, https://doi.org/10.3141/2264-09.

Miranda-Moreno, L. F., A. C. Lahti (2013), 'Temporal trends and the effect of weather on pedestrian volumes: A case study of Montreal Canada', *Transportation Research Part D: Transport and Environment*, 22, 54–59, https://doi.org/10.1016/j.trd.2013.02.008.

Naumann, R. B., A. M. Dellinger, T. Haileyesus, G. W. Ryan (2011), 'Older adult pedestrian injuries in the United States: Causes and contributing circumstances', *International Journal of Injury Control and Safety Promotion*, 18(1), 65–73, https://doi.org/10.1080/17457300.2010.517321.

Öberg, G., G. Nilsson, H. Velin, P. Wretling, M. Berntmann, K. Brundell-Freij, C. Hyden, A. Staahl (1996), 'Single accidents among pedestrians and cyclists', vti, VTI meddelande 799A, https://vti.diva-portal.org/smash/record.jsf?pid=diva2%3A673035&dswid=3785.

Oxley, J., S. O'hern, D. Burtt, B. Rossiter (2018), 'Falling while walking: A hidden contributor to pedestrian injury', *Accident Analysis & Prevention*, 114, 77–82, https://doi.org/10.1016/j.aap.2017.01.010.

Pajala, S., P. Era, M. Koskenvuo, J. Kaprio, T. Tormakangas, T. Rantanen (2008), 'Force Platform Balance Measures as Predictors of Indoor and Outdoor Falls in Community-Dwelling Women Aged 63-76 Years', *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 63(2), 171–178, https://doi.org/10.1093/gerona/63.2.171.

Sabir, M. (2011), 'Weather and travel behaviour', PhD thesis, Vrije Universiteit Amsterdam, Amsterdam, the Nederlands, Ph.D dissertation , https://research.vu.nl/en/publications/weather-and-travel-behaviour.

Saneinejad, S., M. J. Roorda, C. Kennedy (2012), 'Modelling the impact of weather conditions on active transportation travel behaviour', *Transportation Research Part D: Transport and Environment*, 17(2), 129–137, https://doi.org/10.1016/j.trd.2011.09.005.

Schepers, P., B. D. Brinker, R. Methorst, M. Helbich (2017), 'Pedestrian falls: A review of the literature and future research directions', *Journal of Safety Research*, 62, 227–234, https://doi.org/10.1016/j.jsr.2017.06.020.

Schneider, R. J., T. Henry, M. F. Mitman, L. Stonehill, J. Koehler (2012), 'Development and Application of Volume Model for Pedestrian Intersections', *Transportation Research Record: Journal of the Transportation Research Board*, 2299(1), 65–78, https://doi.org/10.3141/2299-08.

Shaaban, K., D. Muley, D. Elnashar (2018), 'Evaluating the effect of seasonal variations on walking behaviour in a hot weather country using logistic regression', *International Journal of Urban Sciences*, 22(3), 382–391, https://doi.org/10.1080/12265934.2017.1403363.

Sim, D., J. Gehl (2019), in and others (ed.), *Soft City: Building Density for Everyday Life* (Washington D.C, USA: Island Press).

Termida, N. A., Y. O. Susilo, J. P. Franklin, C. Liu (2018), 'Understanding seasonal variation in individual's activity participation and trip generation by using four consecutive two-week travel diary', *Travel Behaviour and Society*, 12, 52–63, https://doi.org/10.1016/j.tbs.2017.12.006.

Wetterdienst, D. (2018), 'Weather data obtained from Deutscher Wetterdienst-DWD WESTE-XL', Deutscher Wetterdienst-DWD WESTE-XL, https://kunden.dwd.de/weste/xl_login.jsp, accessed 20240910.

About the authors

Martin Bärwolff works for Autobahn GmbH, the German federal motorway operator. From 2015 to 2024, he was a research associate at the Chair of Mobility Systems Planning at TUD Dresden University of Technology. His research focused on traffic safety and automated methods to measure and analyse traffic. He co-developed OpenTrafficCam, an open-source system for automated recording and analysis of road traffic and co-founded platomo, a start-up specialized in automated and data-driven methods in traffic and mobility.

Regine Gerike holds the Chair of Mobility Systems Planning 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.