Doctoral theses at NTNU, 2022:143

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Winter walking

The impact of pavement surface conditions on pedestrians' walking behavior during winter

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Thesis for the Degree of
Philosophiae Doctor
Department of Civil and
Environmental Engineering

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Trondheim, May 2022

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Summary

This research has aimed to quantify relationships between pedestrians' behavior (and consequences of behavior) and pavement surface conditions during winter. The methods consisted of observational studies with associated measurements and registrations of behavioral adaptations on different winter surfaces and a questionnaire focusing on pedestrians' route choices.

In Norway, there are two service levels for the winter operations of pedestrian and bicycle facilities operated by the Norwegian Public Roads Administration. They are called GsA and GsB. GsA is an implementation of a bare road strategy for pedestrian and bicycle facilities where the pavement surface is kept snow- and ice-free. GsB is an implementation of a winter road strategy for pedestrian and bicycle facilities where a compact snow layer above the pavement is kept even, and gritting is used as a friction-increasing measure when needed.

The main findings from the studies are as follows. If GsA and GsB are compared, when both are maintained as intended, there are generally minor differences with regard to behavior and negative consequences. The major behavioral changes and negative consequences occur when the surface becomes slippery and icy. A significant relationship between pavement surface conditions and pedestrians' route choices was found. More than half of the respondents in the pedestrian survey often or sometimes change the route in the winter compared to the routes they choose in the summer, which is mainly done to avoid slippery areas. The observational study showed a small but significant correlation between route choice and winter operation service level in favor of GsA versus GsB. As the slipperiness of the surface increases, pedestrians respond by reducing their step length. In contrast, the step frequency remains virtually unchanged – except when walking on ice, where there is a small but significant increase in step frequencies. These changes in gait pattern result in increased energy consumption when walking on slippery surfaces compared to asphalt. The difference in energy consumption when walking on GsA compared with optimal GsB is negligible. In general, pedestrians walk more slowly on snow and ice-covered surfaces than on asphalt. The speed differences mean that, on average, 1 min/km longer time is spent when walking on optimal GsB than on GsA and 2 min/km longer time on clean ice than on GsA. Given that close calls can be used as an indirect measure of single accidents and under certain conditions regarding the chosen method and a somewhat limited dataset, it appears that the risk of single accidents can be halved when smooth ice is gritted. The single accident risk is estimated approximately seven times higher on gritted ice than on compacted snow. It seems that unexpected smooth and slippery parts, e.g., ice hidden under loose snow or polished compact snow surrounded by compact snow with high available friction, contributes to many single accidents in winter.

Sammendrag

Målet med denne forskningen har vært å kvantifisere sammenhenger mellom fotgjengeres atferd (samt konsekvenser av atferd) og føreforhold om vinteren. Metodene har bestått av observasjonsstudier med tilhørende målinger og registreringer av atferdstilpasninger på ulike typer vinterføre og en spørreundersøkelse med fokus på fotgjengeres rutevalg.

I Norge er det to tjenestenivåer for vinterdrift av gang- og sykkelanlegg der Statens vegvesen er ansvarlige for vinterdrift og -vedlikehold. De kalles GsA og GsB. GsA er en implementering av en barveistrategi for gang- og sykkelanlegg der fortauet holdes snø- og isfritt. GsB er en implementering av en vinterveistrategi for gang- og sykkelanlegg hvor et kompakt snølag på fortauet holdes jevnt og grusing brukes som friksjonsøkende tiltak ved behov.

Hovedfunnene fra studiene er som følger. Sammenlignes GsA og GsB, når begge opprettholdes etter hensikten, er det generelt små forskjeller med hensyn til atferd og negative konsekvenser. De store atferdsendringene og negative konsekvensene oppstår når overflaten blir glatt og isete. Det ble funnet en signifikant sammenheng mellom fortauets føreforhold og fotgjengeres rutevalg. Mer enn halvparten av respondentene i fotgjengerundersøkelsen bytter ofte eller noen ganger rute om vinteren sammenlignet med rutene de velger om sommeren, og dette gjøres i hovedsak for å unngå glatte partier. Observasjonsstudiet viste en liten, men signifikant sammenheng mellom rutevalg og vinterdriftstjenestenivå til fordel for GsA kontra GsB. Når underlagets glatthet øker, responderer fotgjengere ved å redusere steglengden mens stegfrekvensen forblir praktisk talt uendret – bortsett fra når de går på is, hvor det er en liten, men signifikant økning i stegfrekvensene. Disse endringene i gangmønsteret medfører økt energiforbruk når man går på glatt underlag sammenlignet med asfalt. Forskjellen i energiforbruk når man går på GsA sammenlignet med optimal GsB er ubetydelig. Generelt går fotgjengere saktere på snø- og isdekket underlag enn på asfalt. Hastighetsforskjellene gjør at det i gjennomsnitt brukes 1 min/km lengre tid når man går på optimal GsB enn på GsA og 2 min/km lengre tid på blank is enn på GsA. Gitt at nestenulykker kan brukes som et indirekte mål på eneulykker og under visse forutsetninger med hensyn til valgt metode og et noe begrenset datasett, viser dataene at risikoen for eneulykker kan halveres ved å gruse overflater med blank is. Ulykkesrisikoen er estimert ca. syv ganger høyere på blank is enn på kompakt snø. Det ser ut til at uventede glatte partier som kommer brått på fotgjengerne, f.eks. is gjemt under løs snø eller polert kompakt snø omgitt av kompakt snø med høy tilgjengelig friksjon, bidrar til mange eneulykker om vinteren.

Acknowledgements

This dissertation has been submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of Philosophiae Doctor (Ph.D.).

The work was conducted between August 2018 and November 2021 at the Department of Civil and Environmental Engineering (IBM) at NTNU in Trondheim. The Norwegian Public Roads Administration funded this research. The research was part of their R&D-program BEVEGELSE – Better operation and maintenance to make more people walk and cycle more.

I want to thank my supervisor, Eirin Olaussen Ryeng, for always being very supportive and encouraging and critically reviewing and commenting on my work. I would not have been able to do this work without your guidance. I want to thank my co-supervisor, Helge Hillnhütter, for his work and efforts on Paper II, both with his writing and for exploring literature that at the time was unfamiliar to both of us. I also want to thank my other co-supervisors, Alex Klein-Paste and Yngve Frøyen, for their engaging discussions and general support.

Further, I want to thank the Norwegian Public Roads Administration for giving me the opportunity to pursue a Ph.D. and for funding this research. A special thanks to the project group of BEVEGELSE – Liv Øvstedal, Stein Brembu, Katja Skille, and Bård Nonstad – for their interest and support in my work and for including me in the other parts of BEVEGELSE I was not directly involved in.

I also want to thank my friends and colleagues at IBM for our time together these years.

Oslo, November 22, 2021

Magne Fossum

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Paper II

Fossum, M., Hillnhütter, H., & Ryeng, E. O. (xxxx)

Winter walking – The effect of winter conditions on pedestrians' step length and step frequency. Submitted to *Transportmetrica A: Transport Science*.

Paper III

Fossum, M., Ryeng, E. O. (2021)

Fossum, M., & Ryeng, E. O. (2021). The walking speed of pedestrians on various pavement surface conditions during winter. *Transportation Research Part D: Transport and Environment*, *97*, 102934. https://doi.org/10.1016/j.trd.2021.102934

Paper IV

Fossum, M., & Ryeng, E. O. (xxxx)

Pedestrians' single accidents during winter conditions: An observational study. (Manuscript).

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List of Abbreviations

GsA See list of definitions (Page 2)

GsB See list of definitions (Page 2)

HRM Hierarchical Risk Model

LOS Level of Service

NPRA The Norwegian Public Roads Administration

NSD The Norwegian Center for Research Data

NTNU The Norwegian University of Science and Technology

PSC Pavement surface condition

RCC Rate of close calls

Preface and motivation for the conducted research

This research was funded and administered by The Norwegian Public Roads Administration through the R&D program BEVEGELSE. BEVEGELSE is an acronym for «Bedre drift og vedlikehold for å få flere gående og syklende» which in English translates to "Better operation and maintenance to make more people walk and cycle more." The program was divided into three parts, and the goal was to gain knowledge on 1. Prerequisites and needs for pedestrians and cyclists, 2. Operating methods, equipment, and organization for efficient operation and maintenance of pedestrian and bicycle facilities, 3. Forms of collaboration, contract design, and follow-up of contractors. The current research was a part of the first part. The R&D program started in 2017 and is ended in 2021. During the years the program has lasted, many people and organizations have contributed to increasing the knowledge on the topics[1].

Early during the Ph.D. studies, my initial thought was that surveys and questionnaires would be most appropriate to assess prerequisites and needs for pedestrians and cyclists. However, during my first months, the Norwegian Institute of Transport Economics was hired to conduct two major surveys on the topic[2]. I reasoned that doing a separate survey targeting the same respondents would partly replicate their studies, which I thought to be unnecessary. Meanwhile, I started thinking about how to best supplement these studies. From the literature, I found that quantified relationships between pedestrians' and cyclists' behavior and winter conditions generally were lacking[3]. My impression was also that most research involving active forms of mobility on the topic is focused on cyclists. Therefore, I wanted to focus on pedestrians instead. When investigating the literature further, I found that most studies investigating walking during winter are either experimental, with recruited participants, or studies of naturalistic walking comparing seasonal differences or differences when walking on either uncovered ground or snow/ice. Generally speaking, treating the pavement surface conditions dichotomously is not as practical if winter operation measures other than providing bare pavement surfaces are evaluated. Comparing seasonal differences is interesting, but it might be challenging to isolate the effects of weather/season and pavement surface conditions. Both these issues can easily be controlled for in an experimental setting. The initial thought was to conduct some experiments with recruited participants. However, since so few studies focused on naturalistic walking, I concluded that focusing on this would be most beneficial to the ongoing research and the existing literature.

In summary: the knowledge gap I identified as an area of interest to research was to measure relationships between naturalistic walking and winter pavement surface conditions and evaluate some of its consequences.

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[1] (NPRA, 2021)
[2] I was partly involved in the design of the surveys as described in Section 2.1.1 and Paper I.
[3] (Svorstøl el al., 2017; Veisten et al., 2019).

Definitions

Pavement surface conditions

In this dissertation, the term *pavement surface condition* is defined as the state of the pavement surface (Klein-Paste and Nuijten, Lecture note). Typical surface conditions during winter are loose snow, compacted snow, slush, ice, and asphalt. The surface condition describes the interfacial medium between the pavement and, in this case, the feet of pedestrians and the tires of a bike.

Winter operation and maintenance

This dissertation differentiates between the concepts of winter operation and maintenance.

W*inter operation*s mean the tasks and routines necessary on the road network to ensure that they are in an acceptable standard and function well for the road users' daily use during winter (Øvstedal and Brembu, 2022). Examples of winter operations are snow clearance, salting, and gritting.

M*aintenance* means efforts and activities that take care of the physical infrastructure in a longer perspective (Øvstedal and Brembu, 2022). Examples are maintaining the standard of the road surfaces, ditches, and road equipment.

Levels of Service, GsA and GsB

Until recently, there were mainly two levels of service (LOS) for the winter operations of pedestrian and cyclist facilities operated and owned by the Norwegian Public Roads Administration (NPRA). The Norwegian terms for the LOSs will be used, and they are called GsA and GsB.

Level of service (*LOS*) means the desired result of the operations and maintenance efforts and the descriptions and requirements to the pedestrian and bicycle infrastructure standard (Klein-Paste, Lecture note). To obtain a given LOS, several measures and methods can be used. Typical winter operation measures are snow plowing, scraping, salting, and gritting/sanding.

GsA is an implementation of a bare road strategy for pedestrian and bicycle facilities where the pavement surface is kept snow- and ice-free. The walkways and sidewalks are usually swept by a vehicle with a rotating brush (a front-mounted power broom) for snow clearance. The same vehicle is also equipped with a salt spreader. Salt is applied before and during snowfall to prevent compaction and on wet pavements when there is a danger of freezing. The winter operation method used to obtain GsA is similar to the Swedish method called "sweep-salting." For a description of a similar method and experiences with it, see Bergström (2003).

GsB is an implementation of a winter road strategy for pedestrian and bicycle facilities. Plowing is done for snow clearance, and salt is usually not used as an anti- and de-icing application. Instead, sanding or gritting is commonly used as a friction-increasing measure if the pavement turns slippery due to compaction and freezing. GsB also has several requirements regarding the evenness of the pavement, friction level, and the height of loose snow. In general, the snow above the pavement should be compact and not loose. If anything else is not specified, this dissertation's term "optimal GsB" refers to a pavement surface condition of compacted snow with no ice formation or loose snow above the pavement.

A more comprehensive description of the two levels of service requirements is found in the NPRA's handbook R610 (NPRA, 2012). A third LOS is currently being introduced and will have a lower standard than the previous two (Internal meeting with the NPRA).

Single accidents and close calls

In this dissertation, a *close call* is defined as a pedestrian skidding and clearly losing balance but avoiding falling to the ground by regaining control of the situation. In other words, the pedestrian is about to fall but does not. It follows that a close call is an event in which the pedestrian might had been hurt if the circumstances had been slightly different. Other terms for "close calls" are "near misses", "narrow escapes" and "miss accidents"

On the other hand, a *single accident* is defined as a pedestrian skidding and falling to the ground. Such single accidents are fall accidents which formally can be defined as "an event which results in a person coming to rest inadvertently on the ground" (WHO, 2021).

Summaries of the individual papers

Paper I - Pedestrians' and bicyclists' route choice during winter conditions

Paper I investigated the association between pavement surface conditions and pedestrians' and bicyclists' route choices during winter. We analyzed responses from two surveys in which pedestrians and bicyclists answered questions regarding their route choices in winter environments. We also conducted an experimental study to investigate the association between pavement surface conditions and route choice. The results indicate that pavement surface conditions significantly impact pedestrians' and bicyclists' route choices. Specifically, pedestrians avoid slippery surfaces in general, while bicyclists avoid surfaces with a build-up of loose snow on the pavement. When GsA is available, some pedestrians change their route from GsB to walk on GsA, even when the amount of snow or slush is minimal on GsB. On the other hand, based on the experimental results, a partly ice-covered surface did not deter pedestrians, suggesting that correspondence between actual surface conditions and pedestrians' visual perceptions is an essential factor in their informed decision making.

Contributions:

Magne Fossum: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing – Review and editing, Visualization. **Eirin Olaussen Ryeng:** Conceptualization, Methodology, Critically reviewing, Supervision.

Paper II - Winter walking – The effect of winter conditions on pedestrians' step length and step frequency

In Paper II, the aim was to investigate how changing characteristics of pavement surface conditions during winter influence the experience and convenience of walking. For this purpose, we observed and measured the naturalistic walking behavior of 1551 pedestrians in terms of step lengths and step frequencies on various pavement surface conditions typically associated with winter environments. The results show that step lengths are significantly reduced on snow- and ice-covered surfaces compared to asphalt. Step frequencies are significantly increased on ice compared to asphalt. These changes in walking behavior are likely done to increase stability and reduce the risk of falling on slippery surfaces. However, one effect of these alterations in walking behavior is that the energy consumption of walking is increased. It is plausible that this increases exhaustion, is deemed less attractive, and likely reduces acceptable walking distances during winter.

Contributions:

Magne Fossum: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Helge Hillnhütter:** Conceptualization, Methodology, Formal analysis, Investigation, Literature review, Writing - original draft, Visualization, Supervision. **Eirin Olaussen Ryeng:** Conceptualization, Methodology, Writing - original draft, Supervision.

Paper III - The walking speed of pedestrians on various pavement surface conditions during winter

Paper III aimed to quantify the relationship between pedestrians' walking speeds and various pavement surface conditions typically associated with a winter environment. The purpose was to enable assessments of the effects of different winter operations and maintenance regimes on pedestrians' average travel times. 2 498 pedestrians were timed as they walked a distance with a known length. The pavement surface conditions they were walking on were categorized as asphalt, compact snow, loose snow, gritted ice, and ice. The results show that there is a significant relationship between surface conditions and average walking speeds. When comparing GsA with optimal GsB, it is expected that the average travel times of an average pedestrian will be approximately 1 min/km longer on the latter than the former when walking on flat ground. Compared with GsA, we can expect the average travel times to be approximately 2 min/km longer on clean ice. We argued that data on average travel times should be implemented in cost-benefit analyses to evaluate the effects of different winter operation and maintenance regimes and measures.

Contributions:

Magne Fossum: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing – Review and editing, Visualization. **Eirin Olaussen Ryeng:** Conceptualization, Methodology, Writing - original draft, Critically reviewing, Supervision.

Paper IV - Pedestrians' single accidents during winter conditions: An observational study

In Paper IV, we wanted to estimate the difference in pedestrians' single accident risk between some types of pavement surface conditions typically found in winter environments. We also wanted to evaluate whether using "close calls" as an indirect measure of single accidents is appropriate for studying single accidents among pedestrians during winter. From an observational study of 2 498 pedestrians who walked on sidewalks and walkways with different types of pavement surface conditions, we had registered whether they experienced a close call, single accident, or not. The method was inspired by the Swedish traffic conflict technique. The results indicate that on homogeneous pavement surface conditions, given that close calls can be used as an indirect measure of single accidents, the single accident risk on gritted ice is approximately seven times greater, and on clean ice 14 times greater, than on compacted non-slippery snow. Hence, the risk of single accidents can be halved by gritting an ice-covered pavement. The results also indicate that "hot spots," meaning particularly slippery spots surrounded by non-slippery conditions, are a likely cause of many single accidents during winter. However, the method used in the study has some limitations that must be addressed in future research.

Contributions:

Magne Fossum: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Eirin Olaussen Ryeng:** Conceptualization, Methodology, Critically reviewing, Supervision.

Contributions to the existing literature

The main contributions to the existing literature obtained through the conducted studies are quantified relationships between naturalistic walking behavior (and consequences of alterations in walking behavior) and pavement surface conditions typical in winter environments. A summary of the obtained relationships are as follows:

- There is a correlation between pavement surface conditions and pedestrians' route choices
  - More than half of the pedestrians' who answered the pedestrians survey in Paper I often or sometimes choose different routes in winter than in summer
  - The main reason for choosing different routes is to avoid slippery pavements
  - When GsA is available, a small but significant number of pedestrians was observed to change their route from GsB to walk on GsA

- Pedestrians walk with significantly shorter steps when walking on slippery surfaces compared to non-slippery surfaces. Step frequencies, however, remain virtually the same, independent of the type of surface
  - The average step length on optimal GsB is 5 cm shorter than on GsA
  - The average step length on clean ice is 14 cm shorter than on GsA
  - The average step length on clean ice is 7 cm shorter than on gritted ice
    - Based on and using existing literature, we estimated that the alterations in gait pattern cause a small increase in energy consumption when walking on slippery surfaces compared to non-slippery surfaces
    - Differences in energy consumption when walking on GsA or optimal GsB are neglectable

- Pedestrians walk slower on snow- and ice-covered surfaces compared to walking on GsA
  - The average walking speed on GsA is 1.51 m/s
  - The average walking speed on optimal GsB is 1.40 m/s
  - The average walking speed on 2-8 cm of loose snow is 1.38 m/s
  - The average walking speed on gritted ice is 1.36 m/s
  - The average walking speed on clean ice is 1.26 m/s

- Given that close calls can be used as an indirect measure of single accidents and under certain conditions regarding the chosen method and a somewhat limited dataset, the results from Paper IV indicate that:
  - The single accident risks can be halved by gritting ice-covered pavements
  - The single accident risks are seven times higher on gritted ice than on optimal GsB
  - The single accident risks are 14 times higher on clean ice than on optimal GsB
  - It seems that unexpected smooth and slippery parts, e.g., ice hidden under loose snow or polished compact snow surrounded by compact snow with high available friction, contributes to many single accidents in winter

The main conclusion of this dissertation is:

- There are generally small differences in walking behavior and consequences of walking behavior for an individual pedestrian when comparing GsA and optimal GsB. In the choice of winter operation LOS between these two, it does not seem to matter much which one is chosen, given that both are provided and maintained as intended and described in the handbooks
    - A reservation is made that the conclusion may not apply to certain sub-groups that were not investigated thoroughly, e.g., older pedestrians using walkers, wheelchair users, and people who are visually or physically impaired.

1.0 Introduction

In the later years, walking and cycling have received increased attention in urban planning and design. Walking and cycling have many benefits. Benefits of cycling include that it is more area-effective than relying on car traffic for personal transport, it can reduce congestions, it is beneficial for public health and the economy, and emissions and pollutions can be reduced if more people cycle instead of driving cars (Teschke et al., 2012; Fishman et al., 2015; Gössling et al., 2019). Similarly, walking in cities improves societal health and reduces national health systems costs (Berge et al., 2012; Tight, 2017). Attractive and safe urban walking and cycling environments extend possibilities for more people to live independent lifestyles. Walking, in particular, is especially important since it is the most basic form of mobility that is available to nearly everyone at no cost, hence being the most inclusive form of mobility.

In Norway today, when the whole country is included, throughout the season, and all types of trips are considered, on average, 21 % of the passenger journeys are made by walking, and 5 % are made by cycling (Hjorthol et al., 2014). In northern countries, ice, snow, and slippery surfaces due to low temperatures can influence the convenience of walking and cycling during several months of the year. Walking and cycling are, however, important forms of mobility also in winter times. The modal share of cycling is more sensitive to winter conditions than pedestrian traffic, which is more stable throughout the year (Miranda-Moreno and Lahti, 2013). Lunke and Grue (2018) found the share of cycling to be reduced by 50 % from April – September to October – March in 2013/14 in Norway, indicating a strong dependency between weather or pavement surface conditions and cycling. Similar results have been found in other countries with harsh winters. In the Finish city of Helsinki, the average bicycle share during the summer months was in 2015-16, close to 15 %, while it was less than 5 % during the winter months (Aalto-Setälä et al., 2017).

Public transport users spend close to half of the total travel time from door-to-door as pedestrians, showing a strong dependency between walking and public transport (Hillnhütter, 2016). Walking also remains important to address when aiming to reduce car driving in urban areas during winter times. In a Norwegian study investigating public transport users' valuation of universal design and comfort, Veisten et al. (2020) found the willingness to pay among public transport users to be highest for mitigating slippery pavement surface conditions when evaluating quality factors related to the area surrounding the stop or station. The willingness to pay for non-slippery conditions was higher than the other factors they investigated, like lighting around the stop/station, leaves around the stop/station, gravel/sand around the stop/station, and road surface quality around the stop/station.

Despite the desire among many planners and policymakers to make more people walk and cycle more all year round, winter conditions can affect various aspects of walking negatively. Previous research has shown that pedestrians' risks of injury are higher during winter than during summer. In a Swedish study, Berggård and Johansson (2010) found the risk of single accidents to be almost three times higher when walking on snow and ice than snow- and ice-free ground when the pedestrians did not use any anti-slip device. In another Swedish study, Gyllencreutz et al. (2015) found that among seniors, the number of single accidents is almost three times greater during the winter months than during the summer months. Among seniors in Canada, Shumway-Cook et al. (2003) found that snowy and icy streets can reduce the willingness to walk outdoors. In a Norwegian study, 4/10 stated they would have walked outdoors more often if walkways and sidewalks were better maintained and freed of ice and snow during winter (Johansson and Bjørnskau, 2020).

1.2 Factors affecting the pavement surface conditions during winter

The desired result of winter operation and maintenance is to achieve an acceptable pavement surface condition. The goal is always to maintain, restore, control, or improve the surface condition to an acceptable level to support effective and safe travel. The pavement surface conditions are never truly stable, and over time they will change in a very complex and dynamic manner. At least three different sources that affect the pavement surface conditions during winter can be identified (Klein-Paste and Nuijten, Lecture note); the weather, the traffic, and winter operation and maintenance, as illustrated in Figure 1.

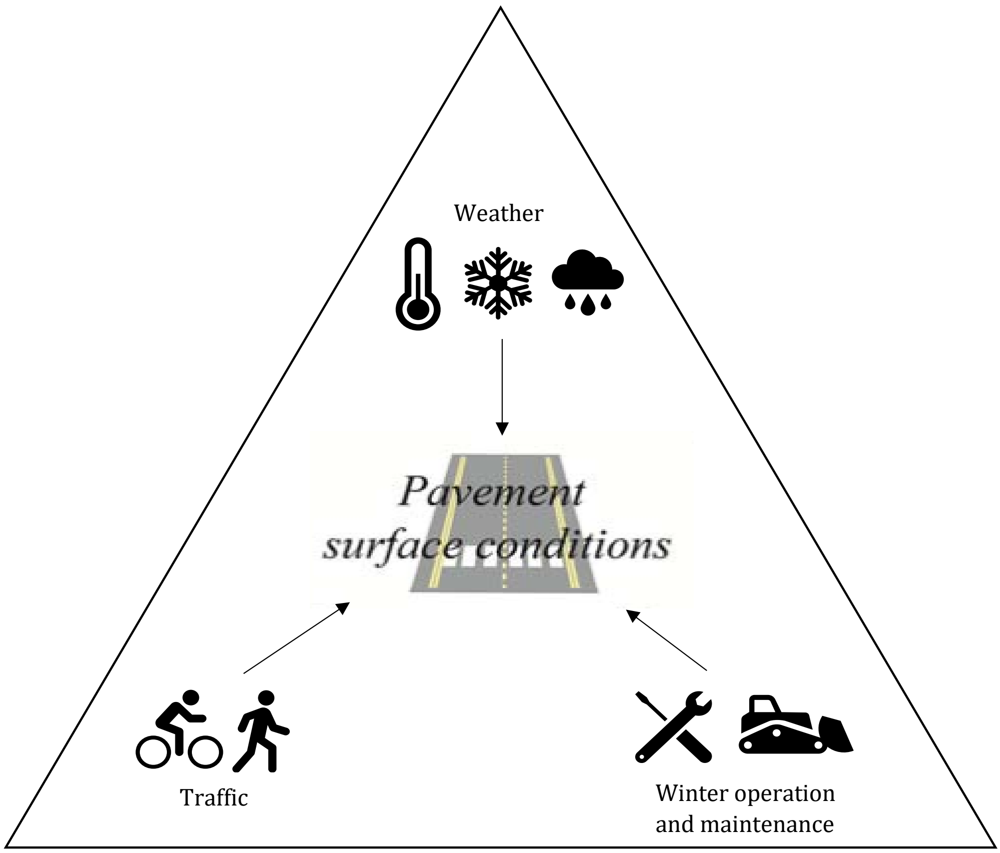

Figure 1 Pavement surface conditions are affected by the weather, traffic, and winter operation and maintenance. The figure is based on and inspired by Klein-Paste (2008).

Weather is the most obvious contributor to changing surface conditions. Snow, rain, freezing and thawing, and wind will all manifest themselves on the surface of a pavement. When all heat and mass fluxes that affect the pavement surface conditions are considered, the actual processes can be quite complex. However, when seen very simplified, snowfalls cause accumulation of snow, rainfall followed by temperatures below 0 °C cause ice formation, and melted snow causes slush on the pavement. These are all simplified causal relationships between weather and pavement surface conditions.

The second contributor to changing surface conditions is traffic. That traffic affects the surface conditions is perhaps most apparent when thinking of cars that, by their weight, can compact loose snow on the road, spray off the water by driving over wet pavements, and blow off sand or snow by turbulences when driving. Cyclists and pedestrians do not have the same blow and spray-off capabilities due to lower weight and speed. However, compaction of snow-covered pavements due to persistent walking and cycling over an area with loose snow is expected. Even persistent crossings on a compacted snow layer may, over time, polish it and turn it to ice under the right circumstances.

The last source that affects the pavement surface conditions is winter operation and maintenance. Winter operations can either be done pro-active or re-active. Re-active winter operation is most likely implemented after a weather incident has occurred or after traffic has affected the pavement surface conditions. Re-active actions are actions taken to regain a desired state of the surface conditions. On the other hand, proactive actions are actions taken to maintain a desired state of the surface conditions. Pro-active actions are typically pre-planned when weather forecasts give the impression that the streets and roads will be negatively affected if no actions are implemented. Typical re-active operational tasks implemented to change the surface conditions during winter are mechanical snow removal by plowing, de-icing by salting, and friction increasing measures like sanding or gritting. Ice prevention by salting (anti-icing and anti-compaction) is a typical pro-active operational task.

1.3 How are pedestrians and bicyclists affected by weather and pavement surface conditions?

Pedestrians and bicyclists affect the pavement surface conditions, as shown in the previous section, but the surface conditions are also likely affecting their behavior. Weather conditions can affect road user behavior directly (Cools et al., 2010), and since weather affects the pavement surface conditions as well, weather can affect pedestrians' and bicyclists' behavior both directly and indirectly, given that the pavement surface conditions are affecting their behavior. The causal relationships are illustrated in Figure 2.

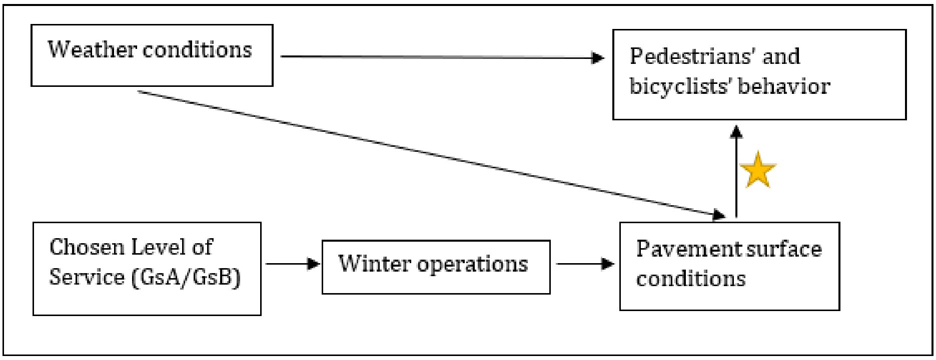

Figure 2 Causal relationships between weather, pavement surface conditions, and road user behavior. The arrow marked by a star is the one of interest in this dissertation and the written papers.

1.3.1 Pedestrians' and bicyclists' behavior as a function of weather conditions during winter

Some examples of weather conditions directly affecting pedestrians' and bicyclists' behavior are the following. The walking speed of pedestrians has been found to directly depend on the air temperature (Bosina and Weidmann, 2017; Liang et al., 2020; Obuchi et al., 2021). As the air temperature decreases, the walking speeds tend to increase. This relationship is thoroughly discussed in Paper III. As discussed there, this behavior probably occurs because when it is cold, people want to avoid spending too much time outside and faster walking helps keep the body temperature stable. Various authors have also studied seasonality's effect on walking speed (Knoblauch et al., 1996; Montufar et al., 2007; Arango and Montufar, 2008). Konblauch et al. (1996) reported faster walking speeds during weather conditions categorized as "snow" than during weather conditions categorized as "dry," while Montufar et al. (2007) reported faster walking speeds during summer than during winter.

At an aggregate level, cold temperatures and precipitation have been found to correlate with reduced walking (Aultman-Hall et al., 2009). Precipitation in the form of snow has also been shown to negatively affect older adults' willingness to walk outdoors (Shumway-Cook et al., 2003). Pedestrians have also been shown to have riskier behavior when crossing streets during inclement weather compared to finer weather (Li and Fernie, 2010). In a study investigating the relationship between weather conditions and cycling ridership, Miranda-Moreno and Nosal (2011) found that precipitation, temperature, and humidity significantly affected bicycle ridership. In general, the rideshares tended to drop when the temperatures decreased and when it was raining. Similar results were obtained by Böcker and Thorsson (2014), who found meteorological data to significantly correlate with trip duration by cycling, mode choice between bicycles and cars, and cycling frequencies.

Because of the direct relationship between weather and road user behavior, caution must be taken when investigating the causal relationship between pavement surface conditions and road user behavior. Suppose care is not taken in the research designs. In that case, it is unavoidable that some of the effects of pavement surface conditions on road user behavior wrongly is assigned to weather conditions and vice versa. This is especially challenging when data is collected between seasons and comparisons are made. For example, it is well established that bicycle shares drop significantly during the winter months compared to the summer months in northern countries (Öberg et al., 1996; Hjorthol et al., 2014; Aalto-Setälä et al., 2017; Lunke and Grue, 2018). However, it is not always clear how much of the drop should be assigned to lower temperatures, cold winds, and increased precipitation and how much various snowy and icy ground conditions contribute to the drop.

1.3.2 Pedestrians' and bicyclists' behavior as a function of pavement surface conditions during winter

Several studies have investigated the relationship between pavement surface conditions and whether to bike or not. In a survey of 1402 current and potential cyclists in Canada, Winters et al. (2011) found that ice and snow-covered surface conditions were a major deterrent on whether to bike or not. Among both regular and potential cyclists, "the route is icy or snowy" was rated the top deterrent among the respondents. Snow-covered ground was also reported by Flynn et al. (2012) to decrease the likelihood of riding a bike for commuting. In the study, respondents reported transportation mode for four seven-day periods in 2009-10, and the authors found that a snow depth of 2.5 cm on the ground reduced the likelihood of biking by about 10 %. The study was conducted in a northern state in the U.S. In another Canadian study investigating characteristics of winter cycling, Amiri and Sadeghpour (2015) found that 71 % of the respondents of their survey did not mind cycling in low temperatures. They identified icy roads as the greatest safety concern in winter cycling, and the respondents' first choice for improving cycling facilities was better snow and gravel removal. This indicates a potential to increase cycling shares during winter by improved winter operations. Indeed, improved winter operations have been shown to have the potential to make more people choose a bicycle as a mode of transport instead of driving a car (Bergström and Magnusson, 2003).

Some studies have investigated the relationship between pavements surface conditions and the decision to walk or not. Rantakokko et al. (2009) found that poor pavement surface conditions correlate with a fear of moving outdoors for many older people. Even though they did not investigate pavement surface conditions during winter directly, there is likely a correlation between the perception of poor street conditions and snow- or ice-covered ground. Shumway-Cook et al. (2003) found that only 6 % of the disabled older adults in their study reported going outside when the pavement surface conditions were icy. In comparison, 47 % of the able older adults reported the same behavior. Johansson and Bjørnskau (2020a) found that 4/10 would have walked outdoors more often if snow and ice removal was improved during winter. Pavement surface conditions have also been found to be one of the most important factors influencing pedestrians' feeling of comfort (Øvstedal and Ryeng, 2002). Therefore, improved winter operations may have the potential to increase walking during winter, at least for older adults who likely are one of the groups most affected when the pavement surface conditions are poor.

Pedestrians' walking speed has also been shown to depend on pavement surface conditions during winter. In a Chinese study investigating how weather affects pedestrians' walking speed in cold environments, Liang et al. (2020) found that pedestrians walk approximately 0.10 m/s slower on snow-covered ground than on clean ground. The authors did not report the amount of snow, whether it was compacted or loose, or whether there was ice on the ground during the measurements. In an experimental study exploring various aspects of gait pattern and the use of anti-slip devices, Larsson et al. (2019) found that the participants tended to walk a bit slower on ice-covered ground with most anti-slip devices compared to their walking speeds at baseline. Cycling speeds have also been shown to depend on the pavement surface conditions during winter. In his master thesis, Sandven (2019) found that cyclists' speeds on compacted snow and asphalt were very similar. However, the speeds were significantly reduced if loose snow or slush were present above the pavement.

1.4 Walkability and bikeability

Lately, the concepts of walkability and bikeability have seen increased usage, and there has been a higher emphasis on soft and active modes of transportation in research and city planning. As sustainable development has received greater attention, car-oriented city planning has been put more in the background. Increased shares of walking as a mode of transport have been shown to have many benefits. Walking benefits public health, the economy, social equity, and the environment (Leyden, 2003; Luberoff, 2016). Similar benefits have been contributed to cycling (Chapman, 2007; Raustorp and Koglin, 2019).

Generally speaking, walkability can be considered as a measure of how friendly an area is to walking. Several factors influence how walkable an area is considered. Some of the most important factors are (Lo, 2019):

- The presence of well-maintained sidewalks and walkways
- Level of universal design
- Mix and diversity in buildings and land-use
- Absence of high-speed car traffic and safety barriers to such traffic
- Stimulating and visually interesting areas in terms of landscapes, trees, and building facades
- Street network connectivity and directness of walking paths
- The perceived or actual security

Based on this list, at least three factors directly depend on the pavement surface conditions: the presence of well-maintained sidewalks and walkways, universal design, and perceived or actual security.

From a winter perspective, how well-maintained a sidewalk or walkway is should be determined by how well snow removal is conducted, the ability to mitigate ice formation on pavements, and the level of available friction on icy and snow-covered pavements. It is reasonable to assume that some groups of pedestrians can cope with worse surface conditions than others. Older pedestrians and pedestrians using aids for their mobility probably have a lower threshold for when the amount of loose snow on a pavement is considered too much compared to younger and fitter pedestrians. Older people have, for instance, lower travel activity – in terms of trips taken and distance traveled – in the winter months than the summer months (Hjorthol, 2013). In this perspective, the pavement surface conditions can be regarded as important for transport equity and universal design. As already noted, winter conditions are associated with higher injury risks in terms of single accidents and especially older people are likely victims of single accidents during winter (Öberg, 1998; Berggård and Johansson, 2010; Gyllencreutz et al., 2015). Based on these findings, it is clear that the actual safety of the pedestrians is directly dependent on the pavement surface conditions. Since the pavement surface conditions can be changed and improved by winter operation and maintenance, there is a potential for such measures to make sidewalks and walkways more walkable by addressing all three abovementioned factors, and thereby, improve the walkability of towns and cities during winter.

The concept of bikeability was developed from the concept of walkability, thereby extending the analyses to both modes of transport (Porter et al., 2020). Some of the most used factors in assessing an area's bikeability are (Castañon and Ribeiro, 2021):

- Type and amount of suitable infrastructure in an area
- The geometric design of cycleways and cycle paths
- Intersection designs and lighting conditions
- Multimodal features and availability of parking areas for bikes
- Bicycle sharing systems
- The quality of the cycling infrastructure
- Mix and diversity in buildings and land-use
- The perceived and actual security
- The aesthetics of the surrounding areas

Of these factors, the quality of the cycling infrastructure and safety concerns are directly dependent on the pavement surface conditions, similarly to walkability. However, it should not necessarily be assumed that an area with a high walkability score automatically has a high bikeability score. Even though the two modes of transport often are treated and spoken of together, they are ultimately two separate modes of transport with distinctive properties and considerations of what, for instance, a safe pavement surface condition is.

1.5 Overall goals and research objectives

Most previous research on the effect of winter conditions on pedestrian and bicycle traffic treats the pavement surface conditions dichotomously. Either the pavement is bare (no snow or ice present on the pavement), or the pavement is snow- or ice-covered. This is unfortunate because the dichotomization might be false. It should be self-evident that, for instance, one can expect different results in terms of safety performance between a gritted and non-gritted ice-covered pavement, or that people will regard a pavement with a high accumulation of loose snow less attractive than a pavement of compacted snow. This is especially relevant if the effects of different winter operational measures are evaluated.

The goal of this dissertation, and the written papers it consists of, is to *investigate the causal relationship between pavement surface conditions and pedestrians' walking* *behavior (marked by a star in Figure 2) and relate this relationship to the chosen Level of Service*. The overall goals of this dissertation are summarized in Table 1.

Table 1 The overall goals of this dissertation

	Research goals
R1	Evaluate consequences* for pedestrians when walking on either GsA or GsB.
R2	Evaluate consequences* for pedestrians when walking on sub-optimal conditions.

*The consequences that are studied are travel times, energy consumption, convenience of walking and single accident risks.

To evaluate consequences for pedestrians when walking on either GsA or GsB is especially interesting in a Norwegian context since these are the two primary service levels of winter operations of pedestrian and bicycle facilities owned by the NPRA. Furthermore, winter operations of pedestrian and bicycle facilities not owned by the NPRA, often rely on the two LOS for their winter operations as well. For this reason, this is essential knowledge as a basis for making informed strategic choices for winter operation standards in Norway. However, since the two LOS can be regarded as quite general, a discussion of their performance in relation to road user behavior and its consequences should be of interest to non-Norwegian readers as well.

This dissertation consists of four papers investigating and measuring some effects of pavement surface conditions on pedestrians' behavior. In contrast to the dichotomization between icy and bare pavements, the pavement surface conditions have been categorized more qualitative and nuanced in the written papers. All four papers included pedestrians as the unit of investigation, while only Paper I also investigated bicyclists' behavior. The main emphasis is, therefore, on walking and pedestrian traffic. The concrete research questions and research objectives of each individual paper are listed in Table 2. By studying route choices, step lengths and step frequencies in Paper I and Paper III the aim was to draw some conclusions regarding the convenience of walking, and energy consumption while walking in winter conditions. Paper II focused on walking speeds, and hence travel times while walking during winter. Last, in Paper IV the aim was to investigate how pavement surface conditions affect single accident risks during winter conditions.

Table 2 Research questions and research objectives of each paper

Research questions and research objectives	
Paper I (i)	How do pavement surface conditions affect route choice decisions during winter?
Paper I (ii)	Does a difference in winter operation service level – that is, between GsA and GsB – affect pedestrians' and bicyclists' route choices?
Paper II	How do pavement surface conditions during winter influence the experience and convenience of walking?
Paper III	What is the association between pavement surface conditions typical in a

	winter environment and pedestrians' walking speed?
Paper IV (i)	Estimate the difference in pedestrians' single accident risk between some pavement surface conditions typically found in winter environments.
Paper IV (ii)	Evaluate whether using "close calls" as an indirect measure of single accidents is appropriate for studying single accidents among pedestrians during winter.

Based on the results and answers to the research questions and objectives listed in Table 2, the main discussion of this dissertation will revolve around the research goals presented in Table 1.

1.6 Theoretical framework – Road user behavior

Through the years, several models have been proposed to explain and predict human behavior in general and road user behavior in particular. In this section, one model that is deemed relevant for the conducted research will be presented, namely the Hierarchical Risk Model (HRM). The purposes of presenting the model are to provide a framework for categorizing the conducted studies and discussing the results. The "understanding" of risk is essential in the model but is not the focus of this dissertation. However, since alterations in walking behavior while walking on various pavement surface conditions during winter, to some extent, likely are made to reduce the risk of falling, the model was deemed relevant as a theoretical framework. The model will be used for explanatory purposes and not for predictive purposes.

In 1988 Van der Molen and Bötticher proposed the Hierarchical Risk Model (HRM) as a framework to describe the perceptual, judgmental and decision-making processes of car drivers at three hierarchical task levels (Van der Molen and Bötticher, 1988). The three levels were termed *Strategical*, *Tactical*, and *Operational*, and were suggested used for understanding driver planning and decision-making as a function of time frame and decision frequency. In the model, assessments related to choices at the strategic and tactical levels are based on perceptions of the external environment. These perceptions are filtered through the road user's experience and understanding and their motivation for the behavior and assessments related to expected or perceived accident risks and expectations related to other factors. Based on these assessments, the road users plan further behavior. This plan, in turn, affects lower-level assessments and behaviors, meaning that choices made at the strategic level influence behavior at the tactical level, which in turn affects behavior at the operational level.

Even though the model was originally intended to explain and predict car driving, the model may also be a useful tool to categorize and explain walking and cycling. How the model can be applied to walking and cycling in winter and how the conducted studies fit in the model will be briefly explained and presented in the following.

At the highest level – the strategical level – decisions such as mode choice, whether to walk outdoors or not, and route planning are made. The concrete maneuvers are planned at the tactical level, for instance, whether to walk over or around a seemingly slippery spot on a sidewalk. These maneuvers are carried out at the operational level. At the operational level, immediate reactions to occurring incidents, such as trying to regain balance when slipping, are carried out as well. Table 3 summarizes the different planning levels and which decisions and behaviors are conducted at each level.

Table 3 Examples of decision-making and execution of behavior at each hierarchical planning level in the HRM

Planning level	**Timeframe**	**Subset of involved tasks and decisions relevant for walking**
Strategical	Long	Route choice, when to travel, mode choice, estimation of travel time
Tactical	Short	Planning of specific maneuvers
Operational	Very short	Execution of maneuvers and emergency reactions

Pavement surface conditions can be assumed to affect travel decisions and behavior on all three levels. At the strategical level, poor snow removal might make travelers reluctant to choose to walk or cycle. Bergström and Magnusson (2003) showed that improved winter operations could increase bicycle trips by 18 % during winter and that improved snow clearance is the most important measure in doing so. Like Rantakokko et al. (2009) and Li et al. (2013) demonstrated, poor street conditions – icy pavements – correlate with a fear of moving outdoors for many older people, hence affecting their decision on whether to travel or not. At the tactical level, the concrete surface conditions the pedestrians or bicyclists faces might require adaptations and decisions to be made on how to maneuver a particular area of the walkway. At the operational level, the adaptations to the pavement surface conditions are carried out, for instance, a change of gait pattern to cope with the identified problematic area of the sidewalk.

The written papers and their placement in the hierarchical risk model are illustrated in Figure 3. Paper I which focused on route choice investigated travel behavior at the strategic level and tactical level. Even though Van der Molen and Bötticher (1988) explicitly characterize route choice decisions as decisions carried out at the strategic level, it is perhaps appropriate to think of the route choice decisions from the experimental study of Paper I as behavior at the tactical level. This is because strategic decisions are often planned before the trip is conducted, and it is reasonable that changing routes in the case of Paper I are decisions made after receiving information about the pavement surface conditions while traveling. However, it is possible that past experiences during the winter the experiment was carried out made some pedestrians and bicyclists learn to expect different pavement surface conditions. In that case, these expectations might have affected the strategic decisions. Since none of the road users who walked or cycled in the experimental area were interfered with, it is not possible to determine their reasonings for certain. The route choice decisions from the surveys, on the other hand, are most appropriate to think of as decisions made at the strategic level. The pedestrians and bicyclists in the surveys were asked to state their route choice preferences at a general level and not asked about any particular trip. Therefore, their answers can be considered to have a longer timeframe and reflect their strategic decision-making.

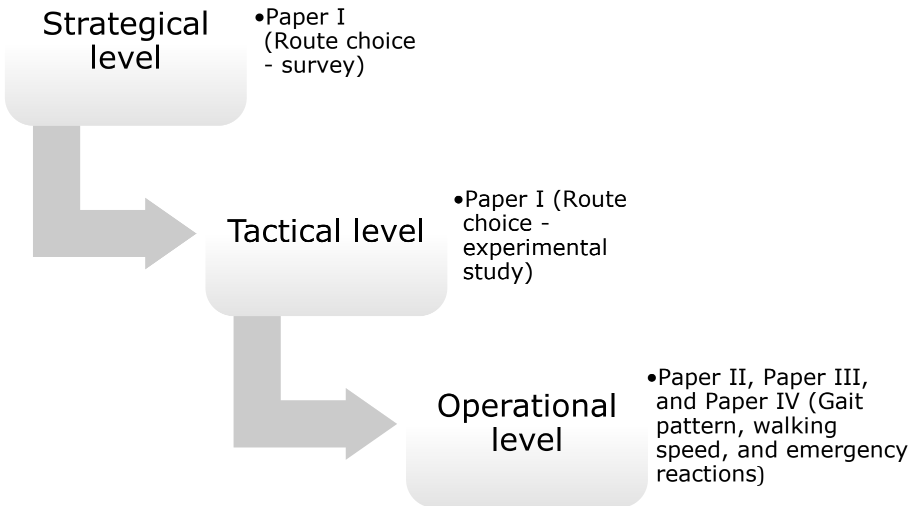

Figure 3 The thesis papers are seen in the context of Van der Molen and Bötticher's (1988) hierarchical risk model of travel behavior.

Paper II and Paper III focused on the gait patterns and walking speeds of pedestrians. While the gait pattern most likely is determined at the tactical level, it is carried out at the operational level – either without extensive reasoning, i.e., unconsciously, or as a result of conscious decisions at the tactical level to, for instance, walk more cautiously if it is slippery.

As illustrated in Figure 4, the chosen gait pattern at the tactical level that is carried out at the operational level has consequences for pedestrians' travel times and accident risks. Single accident risks on various pavement surface conditions was investigated in Paper IV. It is appropriate to think of the likelihood of slipping and falling as partly based on the pavement surface conditions themselves and partly based on the chosen gait pattern while walking on a particular type of pavement surface condition. The reasoning behind the last point is that the friction between the surface and the foot directly depends on the ground's normal force on the foot. Shorter steps increase the normal force and hence the friction. When the steps are shorter, the angle between the foot and the surface is smaller, resulting in a higher normal force. Longer steps will also increase the lateral forces on the foot, increasing the likelihood of slipping on a surface with low available friction. Therefore, it is very likely that the gait pattern affects the accident risk.

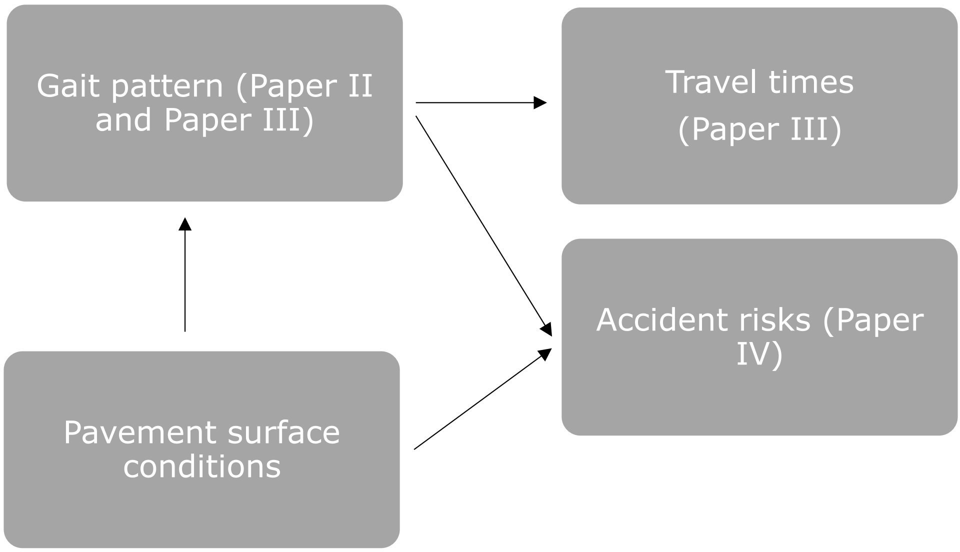

Figure 4 Causal relationships between the pavement surface conditions, the chosen gait pattern at the operational level, and outcomes in terms of travel time and accident risks.

2.0 Research designs and methods of analyses

Common for the research design of all four papers is that manual observation of naturalistic walking behavior was the primary method used for the data collection. As briefly discussed in the Preface, alternative methods and research designs could have been used to study walking behavior related to winter conditions. Most notably, experimental studies and surveys were deemed as appropriate alternatives. The major benefit of surveys and experiments is that it is easier to gain an understanding of the reasoning behind choices, which is far more difficult to grasp through manual observations without interfering with the participants. At the time the conducted studies were planned, two major surveys related to the topic was already ongoing[4]. Instead of making one or more separate survey(s) targeting the same respondents, observational studies were deemed as valuable supplements to them and other similar studies on the topic. While reviewing literature on walking behavior and gait patterns, experimental studies in the lab seemed far more common than field studies of naturalistic walking. This last point was the reason for making observational studies of unaware participants rather than experimental studies. The choice of using manual observations rather than more sophisticated methods for observing behavior are discussed in Section 2.3.1.

Data were collected during two periods, the winter of 2018/19 and 2019/20. The data used in Paper I was collected during the first period, while the data used in Paper II, Paper III, and Paper IV were collected during the second period. All four papers aimed to capture naturalistic travel behavior. Therefore, the observer did not make himself known to any of the pedestrians or cyclists who were observed. To avoid being detected and recognized, the observer was wearing natural clothes and hid the stopwatch used for measurements in Paper II and Paper III from the sight of the road users. The observer was always standing as far as practically possible away from the sidewalks, walkways, and cycleways where traffic was observed and measured. However, the observer was standing close enough to precisely time, measure, and register whatever was the aim for the different studies. One single observer did all the data collections for all four papers. For each study, the same pre-defined procedure was used each time. Therefore, errors due to differences in interpretation between observers are non-existent in the data. Random error, on the other hand, may have occurred. The limitations of the research designs and possible sources of error will be discussed in Sections 2.3.1 and 2.3.2.

Since the methods are thoroughly explained in each paper, only the most important details will be presented, including a discussion of the research methods at a more general level.

2.1 Route choice study

2.1.1 Surveys

The surveys used in Paper I were created and distributed in collaboration with the Institute of Transport Economics. The reason for the collaboration with the Institute of

[4] The results of these surveys are presented in: (Johansson and Bjørnskau, 2020a; Johansson and Bjørnskau 2020b; Aasvik and Bjørnskau, 2021).

Transport Economics was that they were involved in the R&D program BEVEGELSE of NPRA, which also funded this Ph.D. research. The Institute of Transport Economics formulated most questions and handled the distribution of the survey as well as the compilation of the answers. The formulation of the questions presented in Paper I was developed specifically for the purpose of this dissertation's conducted route choice study (except for the questions analyzed in Table 5 in Paper I). The other parts of the surveys are now presented in two reports and one journal paper (Johansson and Bjørnskau, 2020a; Johansson and Bjørnskau 2020b; Aasvik and Bjørnskau, 2021).

The two surveys were created and distributed in 2019. One was aimed at pedestrians, and the other was aimed at bicyclists. Both surveys' respondents were asked questions regarding their daily travel behaviors, their attitudes to operation and maintenance related to their travel behavior, and their background information such as age, gender, and place of residence. They were also asked specific questions related to differences in route choice between summer and winter and their reasons for altering routes. Respondents were asked about their general travel behavior during winter and not about a specific trip.

For both surveys, only pedestrians and bicyclists who stated that they typically walk and cycle during winter were included in the analyses. After this filtering, there were 1677 pedestrian survey respondents and 736 bicycle survey respondents. Descriptive statistical analyses were conducted using SPSS Statistics 26.

2.1.2 Experimental/Field study

To supplement the stated preferences from the surveys, an experimental study was conducted in the fall and winter season of 2018/19. The experiment quantified pedestrian and bicycle traffic on two identical pedestrian and bicycle facilities separated by a 4-lane roadway. Traffic was quantified in the fall when the surface conditions were identical on both sides; this was defined as the reference period. During winter, one side was operated as GsA by using salt for ice mitigation and prevention and sweeping for snow clearance. This resulted in a bare pavement surface with visible black asphalt during the entire period. The other side was operated as GsB by plowing for snow clearance without the use of salt. In practice, a compact or loose layer of snow was allowed to accumulate on the asphalt, depending on the amount of snow. When needed, gravel was used as a friction-increasing measure for GsB.

In winter, the temperature fluctuated around 0 °C. This resulted in Side GsB, where no salt was used, to have varying surface conditions depending on weather and temperature. The surface conditions on this side varied between snow-, slush-, and ice-covered pavement. The amount of snow, slush, and ice on the GsB was relatively modest owing to the weather during the observation period. During this period, the snow depth on the surface was 5 cm or less.

The data were analyzed using binary logistic regression because the outcome variable was binary: The pedestrian or bicyclist walked/cycled on either Side GsA or Side GsB. The pavement surface conditions were included in the regression models as a categorical variable with one value for each of the four states of the pavement surface condition that at some point was present on Side GsB. The state when Side GsA and Side GsB had identical pavement surface conditions – uncovered asphalt during the fall – was the reference category the other states of Side GsB were compared to. The idea was to compare the number of pedestrians and bicyclists that walked or cycled on Side GsB during winter compared to the reference period. The data were analyzed using Stata version 16.

2.2 Observational studies of pedestrians' gait pattern and single accidents

2.2.1 Measurements of pedestrians' step length, step frequency and walking speed

The data was collected between November 2019 and March 2020. Four neighborhoods were chosen as sites for the observations. They were chosen based on both their similarities and differences. They were similar in that the pedestrian volumes were usually high, the infrastructure was similar, and they had low volumes of car traffic. They were, however, different in the sense that the demographics of the pedestrians usually walking at the different sites varied between them. A common characteristic between all four neighborhoods was that the winter operation LOS on different parts of the street network varied. In other words, walkway segments operated as GsA and GsB were present in all neighborhoods. The measurements were not conducted close to any intersections but rather on more extended straight walkways or sidewalks separated from car traffic. Data on the pedestrians' gender, approximate age, whether they were using crampons, walkers, or were rolling strollers, were also registered.

The dataset used in Paper II and Paper III is the same, but the samples used are not identical. The sample used in Paper II is part of the larger sample used in Paper III. Paper III included older pedestrians using walkers for mobility and pedestrians rolling strollers, while these groups were not analyzed in Paper II. Some pedestrians that were walking unrhythmically were also excluded from the sample of Paper II while they were included in Paper III. Lastly, the sample of Paper II only includes pedestrians walking on flat ground, while pedestrians walking on an upwards and downwards slope were part of the sample analyzed in Paper III. The sample size in Paper II is N = 1551 and the sample size in Paper III is N = 2498.

Figure 5 shows how the dependent variables used in Paper II and Paper III were measured and calculated. If one has a specified distance with a known length, knows the time and number of steps a pedestrian uses to walk the specified distance, the pedestrian's average walking speed, step length, and step frequency can be calculated. The term *step frequency* will be used for the number of steps a pedestrian uses per time unit in this dissertation. *Cadence* or *step rate* are synonyms often found in the literature.

For the calculations in Figure 5 to be valid, it is assumed that the pedestrians walk with a constant frequency and step length for the specified distance. Pedestrians clearly violating this assumption by walking unrhythmic were not included in the analyses. To maximize the likelihood that a pedestrian did not violate this assumption, it was ensured that the surface conditions were homogeneous from the start to the endpoint. Another reason for having the surface conditions homogeneous was to find typical values for walking speed, step length, and step frequency associated with a defined type of surface condition. Therefore, the change in any of these quantities of walking when pedestrians walk from one type of surface condition to another or how, for instance, icy spots on asphalt affect them cannot be estimated based on the data.

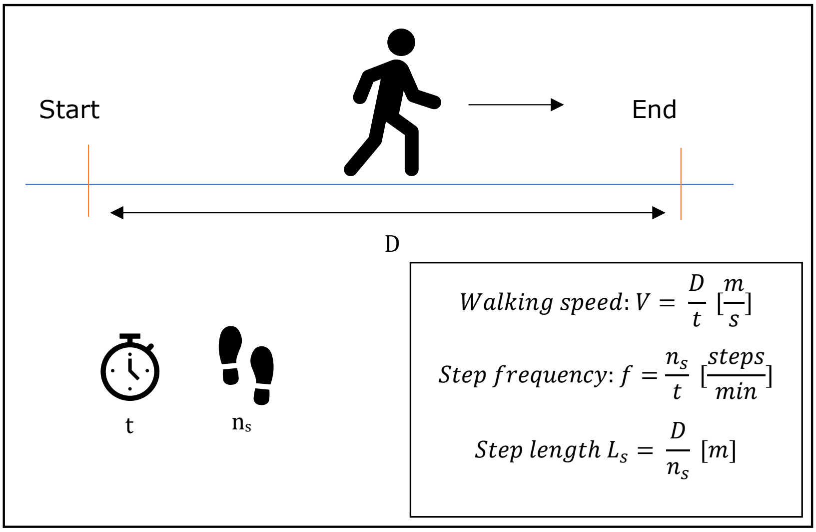

Figure 5 Graphic illustration of the collected data and calculations of walking speed (V), step frequency (f), and step length (L_s). Where D = a distance with known length, t = time used walking D, n_s = number of steps used walking D.

The relationship between the walking speed, step frequency, and step length of a person is:

$$Walking\ speed = Step\ frequency\ \times Step\ length$$

Linear regression was applied as analysis method in both the walking speed study and the study concerning pedestrians' step lengths and step frequencies. The data were analyzed using Stata version 16.

2.2.2 Measurements of pedestrians' single accident risks

The accident analyses presented in Paper IV aimed to find associations between single accident risks among pedestrians and various types of pavement surface conditions during winter. For this purpose, the idea was to use close calls as an indirect measure for single accidents. The inspiration for using close calls as an indirect measure for single accidents was found in the Swedish traffic conflict technique (Sakshaug et al., 2013; Laureshyn and Várhelyi, 2018).

The primary motivation for using close calls as an indirect measure of single accidents was that they occur way more often than single accidents. The underlying assumption for this approach to be valid is that single accidents and close calls are causally related. If that is the case, the proportion of single accidents and close calls are identical on each pavement surface condition, but the absolute number of both differs. Therefore, the relative difference in safety performance between the pavement surface conditions can be calculated, provided the assumption is valid.

Two criteria for recording close calls were applied. The first criterion was that the close call occurred between the start- and endpoint illustrated in Figure 5. The second criterion was that the time-measuring of the pedestrian experiencing the close call had started before the close call occurred. The second criteria ensured that the pedestrian experiencing the close call would have been included in the dataset even if they had not experienced the close call, thereby providing the possibility to reasonably indicate a measure of exposure. Because of the research design, the distance traveled by any of the pedestrians was unknown. Ideally, a standard measure of single accident risk on pavement surface condition (PSC) x can look like:

$$Single\ accident\ risk\ (PSC\ x) = \frac{Number\ of\ single\ accidents\ (PSC\ x)}{Distance\ walked\ by\ pedestrians\ (PSC\ x)}$$

Since the walked distance is not known and close calls is used as an indirect measure of single accidents, the simplified measure of "single accident risk" – which more correctly should be referred to as the rate rather than the risk – on pavement surface condition x using close calls as an indirect measure, is:

$$Rate\ of\ close\ calls\ (PSC\ x) = \frac{Number\ of\ close\ calls\ (PSC\ x)}{Total\ number\ of\ observed\ pedestrians\ (PSC\ x)}$$

This expression does not calculate the risk of single accidents but rather the rate of close calls. The abbreviation RCC will be used for the rate of close calls. If the assumption that close calls and single accidents are causally related is valid, RCC can be used to evaluate the relative safety performance of the investigated pavement surface conditions.

The idea was that enough data on close calls could be collected to enable quantitative analyses – for example, binary regression – on single accident risks on different types of pavement surface conditions. As it turned out, enough data could not be collected to enable regression analyses, and the more simplified calculation using RCC was chosen instead.

Since actual single accidents are rare incidents, the strict criteria in which close calls were registered were not complied with for the single accidents that were observed. All single accidents observed while collecting the data were registered. For this reason, it is not possible to assess the exposure in the data of observed actual single accidents. When a single accident occurred, a description of the spot where it happened was immediately written down with other relevant information like the person's approximate age, gender, and the sequence of events.

2.3 Discussion about the chosen methods and research designs

With increased digitalization, more and more research rely on digital data collection techniques that are often both time- and cost-efficient. Examples of techniques that could have substituted the chosen manual observational designs are data collection using video recordings, GPS data, or drone technology. These techniques and methods were considered but eventually scrapped in favor of simple manual observations. In this section, alternative methods and the reasons for choosing the manual observations will be discussed.

2.3.1 Alternative methods to the manual observations

The major benefit of manually collecting the data is that "you are staying with your problem" and can learn and identify areas of interest that are not always easy to think of beforehand. Sometimes the most interesting stuff happens where you are not expecting it. Hence, being out observing enables the formation of hypotheses and ideas for future studies.

The most straightforward alternative method that could have been chosen instead of manual observations is video recordings. A camera could have been installed on the side of the sidewalks and walkways and record pedestrians and cyclists as they walked and cycled along the area of interest. The camera could have been installed to ensure that the identity of any individual pedestrians or cyclists had not been possible to determine. The walking speeds, step lengths, step frequencies, and accident incidents could then have been automatically, semi-automatically, or manually extracted from the recordings on a computer.

Video recordings were not deemed suitable for Paper II and Paper III because it was not always possible to plan where to do the observations beforehand. Even though data was only collected in four specified neighborhoods, the actual sidewalk or walkway the measurements were conducted on was determined the night before or even on the same morning as the observations took place. The criteria for where to do the measurements were the quality of the pavement surface conditions and what type of surface condition needed more observations for quantitative analyses to be reliable. During a typical day of observations, two or three of the neighborhoods used as study sites could be visited, and more than one sidewalk or walkway in any particular neighborhood could be observed at different times throughout the day. If a similar strategy was used, only using video recordings, several cameras would have had to be installed and taken down each day (because of where to place them and battery time). Therefore, it was not considered so much more time-efficient. The data would also have had to be extracted from the video recordings, perhaps, making this particular method even more time-consuming than the chosen method.

For Paper I, however, video recordings would have been the preferred method for the data collection. In Paper I, the observations were conducted along the same roadway for several days. Recording it and then extracting the data would have allowed the observational period to be extended. This method was not chosen because collecting data through video recordings is considered sensitive and in Norway requires an application to NSD. The time for planning the study was too short for such an application.

In hindsight, the observations for the accident analyses in Paper IV would also have benefitted from video recordings of the close calls. Because of the strict criteria in which close calls were registered, outlined in Section 2.2.1, some close calls were lost and not registered. If the data had been manually extracted from video recordings, the exposure could have been controlled for more easily, and more data could have been collected and analyzed. Further, video recording would have enabled the possibility to run the videos of the close calls multiple times, thereby perhaps identifying details not possible to detect during real-time observations.

Using GPS data in transport analyses has seen increased use in the later years. The benefits of such methods are that data from many individuals can be analyzed over more extended periods and larger spatial areas. The limitations of using this method for the data collection in any of the conducted studies is that the pavement surface conditions the pedestrians or cyclists were measured on never could have been definitively determined. Since having control of the actual pavement surface conditions was considered paramount, using GPS data was never considered a real alternative.

The last alternative method for the data collection that was considered was using drone technology. The benefit of drones is that you get a bird's eye view of the data you are collecting, and unlike GPS-data get visual information. The birds-eye view would have enabled more than one sidewalk or walkway to be monitored simultaneously. The visual information would have enabled the pavement surface conditions to be partly determined, definitively more so than GPS data would have enabled. The biggest downside to this method is the limited air-time due to the batteries. The drones that could have been made available for this research can fly for about 30 minutes before the batteries must be charged. However, limited observational time per turn could have been compensated by the fact that a larger area would have been possible to observe simultaneously, as discussed. Using drones for the study of walking speeds would have been a good substitute for the chosen method. However, it is possible that measuring step lengths and step frequencies could have been problematic from the bird's eye view. Therefore, collecting the data simultaneously by manual observations and manual registrations was, perhaps, most efficient after all. Another challenge is that flying drones for research purposes in Norway requires a license to operate them. Drone technology would have been a good substitute in at least three of the studies – except for Paper II, but ultimately, this method was not chosen. Drone technology will likely see increased use in similar studies in the coming years.

2.3.2 Sources of error – observational data

There are a couple of potential sources of error relevant to the conducted observational studies. First, using a stopwatch for the time measurements in Paper II and Paper III might be associated with some errors. Studies using direct manual timing have been found to, on average, report 5 % higher walking speeds than studies using manual data extraction from video recordings (Bosina and Weidmann, 2017). Therefore, there is a possibility that all reported walking speeds in Paper III are a bit overestimated. Since one observer did all the measurements using the same procedure each time, any relative error between the measurements on each type of pavement surface condition should be minimal.

Second, when counting the number of steps used to walk a certain distance, there is a possibility that half a step is missed as the pedestrian crosses the start- and endpoint of the registration area. To minimize this source of error, measurements over too short distances were avoided. The "measuring distance" was also included as a control variable in the regression models used in Paper II.

The observer made all age and gender categorizations. Some pedestrians and cyclists may have been wrongly categorized. Ideally, a sample of the road users should have been asked about their age and gender, and their responses should have been compared to the observers' own categorizations. This would have made it possible to determine the reliability of the observations. Also, whether the pedestrians were wearing crampons or not was determined by observation. This was very challenging to detect visually and was most times determined by hearing the crampons hitting the asphalt or the ice. Likely, some of the pedestrians in the observational studies that were categorized as not wearing crampons did wear it.

Another source of error typical for observational studies is the tiredness of the observer(s). When getting tired, concentration and focus are inevitably reduced. This can cause measuring errors and sloppy registrations. It is very difficult to determine if such flaws have affected the obtained results. Even if there was no strict plan for observations and pauses in the research designs in neither study, the observer took breaks when needed.

3.0 Summary of the results

In this section, the results from the conducted studies will be presented. The results are presented thematically. Only the main results from each study are presented. The reader is advised to read the individual papers for nuances and a deeper review of the results.

3.1 Route choices

Approximately 50 % of the pedestrians and cyclists who answered our surveys reported very often or sometimes choosing different routes during winter than they normally would have chosen during summer. Among pedestrians answering the survey, older people and women are more likely to choose alternative routes than younger people and men.

To answer the first research question, "How do pavement surface conditions affect route choice decisions during winter?" the respondents were asked to state the main reasons for them choosing alternative routes during winter. For both pedestrians and cyclists, pavement surface conditions are the main factor making them choose alternative routes. Alternative reasons that also are prominent in winter environments like inadequate lighting, conflicts with other road users, and air pollution were not as important as pavement surface conditions. There were some differences between pedestrians and cyclists concerning what conditions made them choose alternative routes. Generally speaking, slippery surfaces are avoided by pedestrians and are considered a bigger problem for them than for cyclists. Previous research has shown that older people consider ice prevention more important than snow removal (Wennberg, 2009). The same conclusion can be drawn from the survey regarding route choices. The results also show that ice is somewhat more deterrent for older pedestrians than younger pedestrians. Cyclists are more concerned with loose snow on the pavement, and 1/5 of cyclists choose alternative routes due to slippery pavements. Even though slippery surfaces are what pedestrians try to avoid the most, almost 2/5 avoid pavements that are laborious to walk on due to snow.

Figure 6 shows the result from the experimental study. It shows that the probability of walking on a pavement was lower when it was snow- or slush-covered compared to if it was uncovered, given that a bare pavement was available within a reasonable distance. The result suggests that GsA is preferable to GsB for a significant but small number of pedestrians. When the pavement of Side GsB was partly ice-covered, there were no changes in its usage from the reference period. Any effect of winter operation LOS on bicyclists' route choice was not found through the experimental study. The number of cyclists was equal for the two alternative routes in the reference period and the period with unequal pavement surface conditions due to a difference in winter operation LOS.

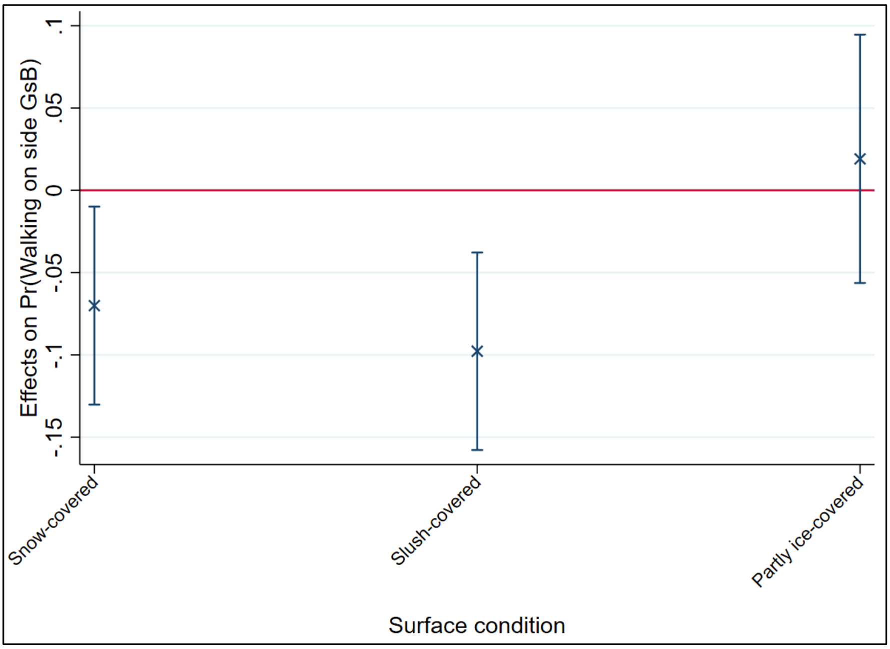

Figure 6 Average marginal effects with a 95% CI. The figure shows the discrete change in the number of pedestrians walking on Side GsB for the different surface conditions, compared to the base level, that is, the reference period when Sides GsB and GsA both had a bare asphalt surface.

3.2 Other analyses and findings based on the route choice dataset

A question not analyzed in any papers but that were asked the respondents of the pedestrian survey in Paper I, is presented in Table 4. As seen, almost 80 % of the pedestrians answering the question claim to spend more time walking a given route during winter than they do during summer. Given the relationship between air temperature and walking speeds, it is reasonable to assume that walking speeds would increase during colder winter temperatures, hence reducing travel times (Bosina and Weidmann, 2017; Obuchi et al., 2021). However, if pedestrians do spend more time walking in winter, as they claim, worse pavement surface conditions during winter is the likely reason for this.

Table 4 Stated time-use walking during winter compared to summer by pedestrians answering the pedestrian-survey presented in Paper I

	In cases where you walk the same route in winter as in summer, do you spend more time in the winter? [%]
Yes	78.2
No	12.1
Don’t know	9.7
N	1677

When asked to give an estimate in percent of how much more time the respondents spend walking a route in winter compared to the time they spend walking the same route in summer, the average estimate was 21.2 %[5] increased time in winter (n=1252, Std. dev. =10.54). 70 % of the respondents reported spending between 10-30 % more time walking in winter conditions. The fact that so many pedestrians claimed to spend an increased time walking in winter conditions was part of the motivation to conduct the study reported in Paper III that investigated the association between pavement surface conditions during winter and walking speed/travel time.

3.3 Step length, step frequency and walking speed

In Figure 7, Figure 8, and Figure 9, the associations between pavement surface conditions and pedestrians' step length, step frequency, and walking speed are shown. All reported results are on flat and even ground. As seen, pavement surface conditions during winter significantly affect pedestrians' gait patterns. The pavement surface condition called "Asphalt" in the two papers is a GsA LOS, while the pavement surface condition called "Compact snow" is an optimal GsB LOS.

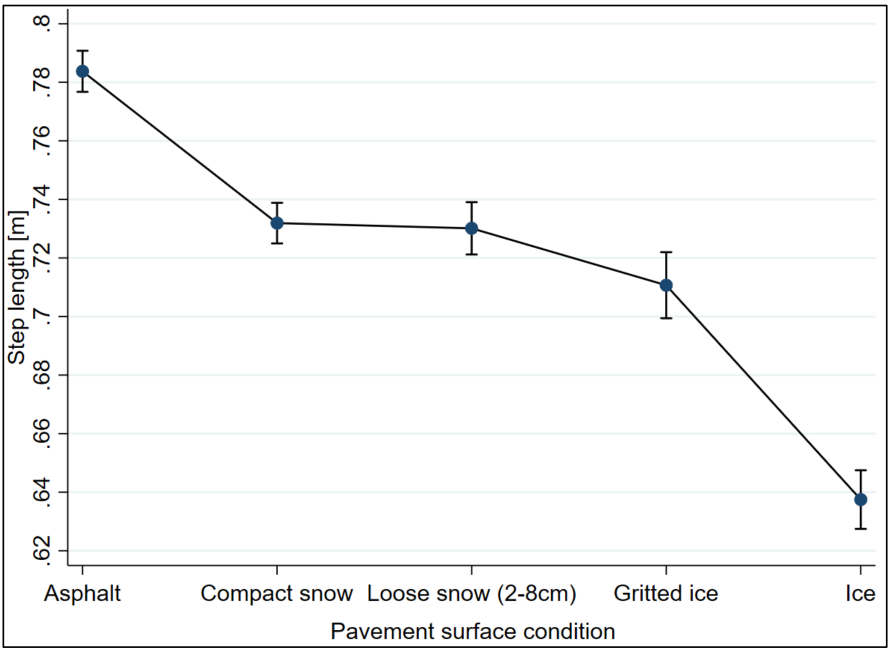

Figure 7 The association between pavement surface conditions and step length.

[5] In the example given to the respondents about how to calculate the increased travel time in percent, 20% was the number used as an example. Since the average estimate is close to the example given, this has likely affected the respondents' estimations of their increased travel time. Therefore, the reported 21.2% increased travel time should be evaluated, keeping this in mind.

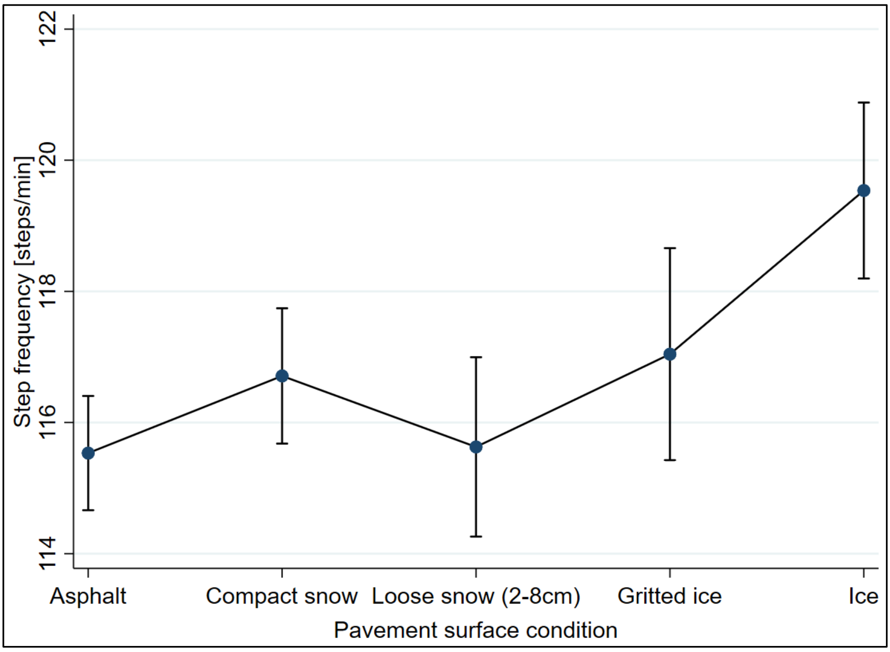

Figure 8 The association between pavement surface conditions and step frequency.

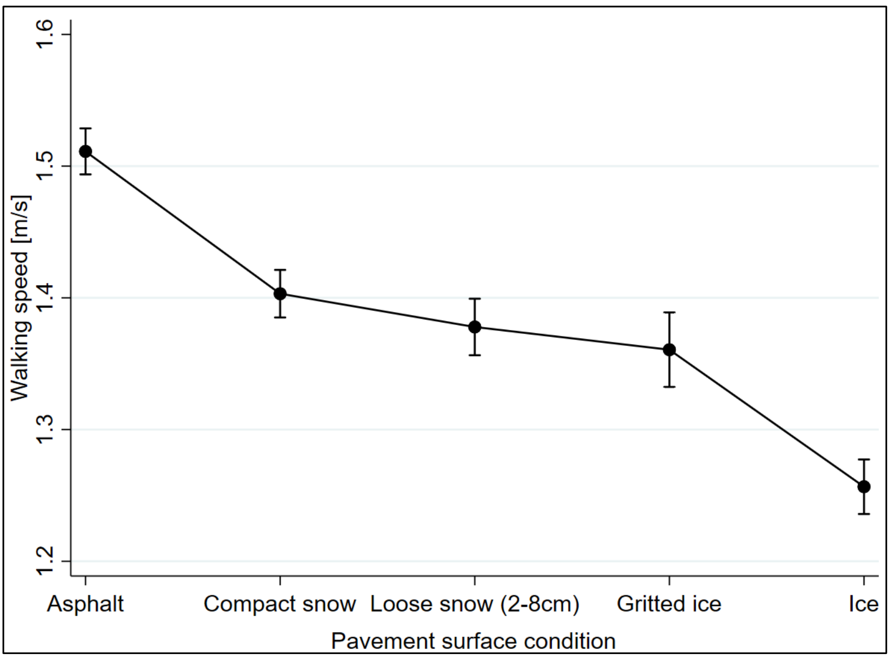

Figure 9 The association between pavement surface conditions and walking speed.

Slippery surfaces due to ice are associated with pedestrians walking with shorter steps and increased frequency compared to how they walk on asphalt. One consequence of the changed gait pattern is that pedestrians walk slower on ice than on asphalt. On average, pedestrians spend approximately 2 min/km longer time walking on ice than on asphalt. Gritting an ice-covered pavement will make pedestrians walk with approximately 7 cm longer steps and a small decrease in step frequency. The changed gait pattern results in approximately 1 min/km shorter travel times on gritted ice than on ice. If GsA is compared to GsB, GsB is associated with pedestrians walking with approximately 5 cm shorter steps and no change in frequency, resulting in approximately 1 min/km longer travel times. When comparing the gait patterns and walking speeds on the pavement surface conditions compact snow, loose snow, and gritted ice, their differences are small and mostly insignificant.

Paper II discussed other effects than walking speed and travel times due to various pavement surface conditions during winter. By analyzing the measured step lengths and step frequencies in the context of results obtained by Zarrugh et al. (1974), changes in energy consumption while walking could be estimated. The changes in gait pattern result in minor increased energy consumption when walking on optimal GsB, a small amount of loose snow, or gritted ice, compared to GsA. Walking on ice, increases energy consumption by between 5-10 % compared to walking on GsA.

Neither in the analyses of Paper II nor Paper III were any sub-groups of pedestrians found to be differently affected by pavement surface conditions than others. For instance, pedestrians using walkers for mobility had approximately the same walking speed reduction as younger, fitter pedestrians when walking on ice compared to asphalt.

3.4 Single accidents

Figure 10 shows the number of observed close calls on each type of pavement surface condition analyzed. In Table 5, the RCCs on each type of pavement surface condition investigated are presented.

Figure 10 Observed close calls on each type of pavement surface condition.

The general trend seems to be that the accident risks increase as the pavement's slipperiness increases, as one would intuitively expect. On loose snow and asphalt, no close calls were observed. On non-slippery compact snow, the calculated RCC is 0.4 %. On gritted ice and ice, the calculated RCCs are 3 % and 6 %, respectively.

Table 5 Rate of close calls (RCC) on each type of pavement surface condition based on the number of close calls related to the total number of observations

Pavement surface condition	Number of pedestrians	Number of close calls	Rate of close calls (RCC)
Asphalt	662	0	0 %
Loose snow	314	0	0 %
Compact snow	685	3	0.44 %
Gritted ice	476	14	2.94 %
Ice	361	22	6.09 %
Total	2 498	39	1.56 %

In total, 11 single accidents were observed in the observational period this winter. Eight of them occurred on a type of pavement surface condition, most likely perceived as compact snow, one on perceived loose snow, and two on gritted ice (see Figure 11). The common feature between all the observed single accidents was that the pavement surface conditions were not homogenous where they occurred. All single accidents occurred on a particularly slippery spot, surrounded by non-slippery surface conditions. For this reason, the perceived pavement surface condition is a description of the surrounding surface conditions of where the accidents occurred.

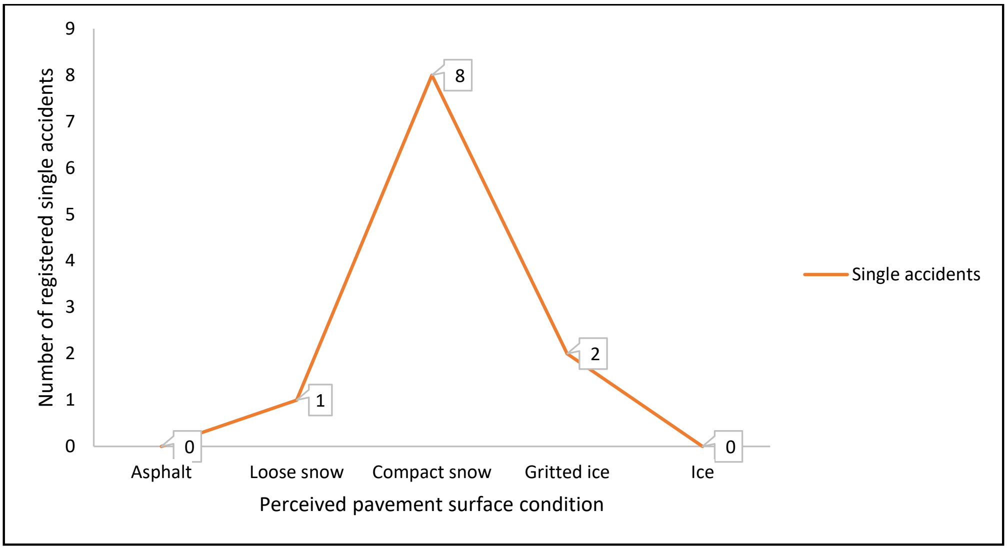

Figure 11 Observed single accidents on pavement surface conditions perceived as those in Figure 10.

4.0 Discussion

4.1 Comparison between GsA and GsB

When evaluating the results from the papers and seeing them in relation to each other and the existing literature, a response to R1: "Evaluate consequences for pedestrians when walking on either GsA or GsB" can be formed.

Perhaps the main reason why one would think that some pedestrians prefer GsB to GsA is that salt is usually required to maintain GsA. Extensive use of salt can deter the pavement (Karlsson, 2019), cause environmental problems (Marvin et al., 2021), lead to corrosion on bikes and infrastructure, and irritate shoes and animal paws. For these reasons, it is plausible that some pedestrians do prefer an unsalted pavement surface, i.e., GsB, even if GsA is preferable on other measures. Therefore, the first question that needs answering when comparing GsA to GsB is, what are pedestrians' attitudes towards salting pavements?

Johansson and Bjørnskau (2020a) asked the respondents in a survey investigating pedestrians' attitudes to operation and maintenance[6] to evaluate the following statements: "Too much salt is used on sidewalks" and "Too much salt is used on walkways and cycleways where I live." The respondents gave their evaluation on a seven-point scale, ranging from 1 = "totally disagree" to 7 = "totally agree." The respondents' evaluations were very similar to the two statements, so only their responses to the first one will be presented. Of the respondents, 21 % did not know or said it was not relevant, 35 % gave a score of 1 or 2, 18 % gave a score of 6 or 7, and 26 % gave a score of 3-5. Therefore, the weight of the answers tips in favor of pedestrians disagreeing that too much salt is used on sidewalks, walkways, and cycleways. There are no significant differences between men and women or older and younger people as to whether they think the amount of salt used on sidewalks is too much. An interesting point to discuss is the formulation of the statements themselves. When presenting respondents with a statement they can agree or disagree with in a survey, there is a tendency that many that do not have a specific opinion about the phenomenon asked about agree to the statement rather than answer "don't know", or similar (Hellevik, 2009). For this reason, those agreeing to the statement may consist of two groups, those who actually agree and, in addition, someone without any clear opinion about the statement. Therefore, it is plausible that fewer people agree that too much salt is used on pavements, walkways, and sidewalks, than the results presented above indicate.

In a study investigating sweep-salting in the Swedish city, Karlstad, Niska and Blomqvist (2015) found that the public was more positive about using salt on cycleways after sweep-salting had been introduced than they were before. Suppose similar attitudes can be expected for the use of salt on walkways. In that case, pedestrians can be expected to be more positive to GsA as they have gained experience walking on such pavements regularly. A similar result was found in a recent Norwegian study, where people reported to be more positive to GsA after it had been implemented and the amount of salt had

[6] This is the same survey in which the questions analyzed in Paper I were included.

been adapted to local conditions than before its introduction (Karlsson, 2019). Based on the studies investigating peoples' attitudes towards salting of walkways and sidewalks, it seems that more pedestrians are positive to it than negative to it beforehand, and their positive attitudes seem to increase as they get used to it.

The next question that needs answering when comparing GsA to GsB is, what are pedestrians' attitudes towards a pavement of compacted snow, i.e., GsB? Johansson and Bjørnskau (2020a) found that a pavement of compacted snow is associated with very few difficulties for pedestrians. On a five-point scale where 1 = "not difficult at all" and 5 = "very difficult," 80 % of the respondents gave a score of 1 or 2 to the statement "how difficult is it for you to walk on a pavement of compact snow". Further, 20 % of the respondents gave a score of 4 or 5 to the statement "how often do you walk more cautiously on compacted snow," when 1 = "never" and 5 = "very often." Even fewer reported changing their route on such conditions. Thus, a large majority of pedestrians are not negatively affected and report not altering their walking behavior when walking on GsB. There are no clear differences between genders and age groups in their evaluations of GsB.

To supplement these stated preferences, GsA and GsB should be compared through the empirical findings of walking behavior on pavements operated as either GsA or GsB. At the tactical level, according to the HRM (Van der Molen and Bötticher, 1988), pavement surface conditions are suggested to affect the route choice of pedestrians. The experimental study in Paper I showed that a small but significant number of pedestrians alter their route choice to walk on GsA instead of GsB. This preference manifested itself in a 7-10 percentage point decrease in the number of pedestrians walking the route operated as GsB when a pavement operated as GsA was available nearby. The reason that some pedestrians did alter their route choice can, perhaps, be explained by their strategic or tactical assessments. If some pedestrians considered the costs of walking on Side GsB greater than the costs of walking on Side GsA, these pedestrians would likely alter their route choice. At least two factors can be associated with pedestrians' perceiving the costs of walking on Side GsB higher than Side GsA, namely, comfort and safety concerns. Snow and slush are probably by some regarded as more uncomfortable to walk on than asphalt, and some pedestrians likely consider asphalt as safer to walk on than snow-covered ground. However, many pedestrians did not alter their route choice, suggesting that the snow and slush were unproblematic and not associated with higher costs than walking on asphalt for them.

Given that the route choice most likely is the first travel behavior that changes due to a perception of insecurity by pedestrians – more so than whether the trip is conducted, mode choice, and when to travel (Backer-Grøndahl et al., 2007), travel behavior at the strategic level in the HRM is probably quite insensitive to whether GsB or GsA is supplied. The arguments for this are the small effect size of pavement surface conditions on route choice and the stated preferences reported by Johansson and Bjørnskau (2020a). It is, therefore, questionable if one should expect more people to walk more and make mode choices in favor of walking by supplying more GsA instead of GsB. However, if the LOS gets worse than optimal GsB, it is reasonable to assume that the effects of pavement surface conditions on strategic and tactical travel behavioral choices will increase. The results from the surveys support this assumption, but this was not investigated by measurements of real-life travel behavior at the strategic level.

After the strategic decisions are made and the pedestrian walks on any given pavement surface condition, they make tactical decisions manifesting themselves in operational behavior. As seen from the results of Paper II, this operational behavior is not the same when a pedestrian is walking on GsA as GsB. Compared to walking on GsA, walking on GsB is associated with a more cautious gait pattern. Pedestrians walking on GsB walk with shorter step lengths than they do on GsA. There are no changes in the pedestrian's step frequency, so the changes in walking behavior result in slower walking speeds. Even if these differences are significant, they are small. On optimal GsB, pedestrians, on average, walk with 5 cm (-7 %) shorter steps and walk 0.11 m/s slower than on GsA. A 0.11 m/s difference in walking speed means that the increase in travel time is about 1 min/km. For an individual pedestrian, this increase in travel time might be regarded as neglectable. However, as discussed in Paper III, the aggregated effect might not be. Another consequence of changes in operational walking behavior, in terms of changes in step length and step frequency, is that it might affect the energy consumption while walking. As seen from Paper II, the increased energy consumption of walking on optimal GsB is less than 5 % compared to walking on GsA, when it is assumed that the chosen gait pattern on GsA is the gait pattern with the lowest energy consumption. Lastly, accident risks on GsA and GsB were investigated through an indirect measure of single accidents using close calls. No close calls on GsA were observed throughout the observational period. On optimal GsB, the RCC was found to be 0.44 %. None of these differences are drastic for an individual pedestrian, even if GsA scores a bit better on all measures.

Based on these evaluations of GsA and GsB, it is tempting to conclude that, for an individual pedestrian, it does not matter much whether GsA or GsB is supplied. From a winter operation and maintenance perspective, this might be regarded as positive. In general, supplying GsB is cheaper than GsA, and as discussed, salt, which is required to supply GsA has many negative side effects associated with it. Reducing the amount of salt and lowering operational costs are positive both for the economy and the environment. However, a reservation must be made for this conclusion to be true. The conclusion may not apply to certain sub-groups that were not investigate thoroughly, e.g., older pedestrians using walkers, wheelchair users, and visually or physically impaired people. Older pedestrians using walkers were included in the study of pedestrians' walking speed. These pedestrians were not more negatively affected by slippery pavement surface conditions than the rest of the sample. In other words, their speed reduction when walking on GsB and ice was not significantly different from the speed reduction of the other pedestrians in the study. The number of older pedestrians using walkers for mobility in the sample was limited, so more data on these users, as well as other groups that are likely to be more negatively affected than the general population, should be investigated further before any conclusive statements are made regarding supplying GsA or GsB.

4.2 Sub-optimal conditions

In the previous section, GsB was evaluated when it has a standard according to the guidelines, meaning when it is close to optimal or optimal. It might be challenging to maintain this LOS in real life when weather and traffic have deteriorated the pavement over time. Therefore, the next question is: how do snow- and ice-covered pavement surface conditions with smaller and greater deviations from the optimal GsB affect pedestrians?

The results from Paper II and Paper III indicate that deviations from GsB in terms of increased snow depth (2-8 cm loose snow) and reduced friction (gritted ice) have a minor impact on pedestrian's operational behavior and, therefore, travel times and energy consumption. The increased travel time on these sub-optimal conditions is in the order of magnitude of 10-20 sec/km compared to GsB. The increased energy consumption when walking on this amount of loose snow or gritted ice is neglectable. The fact that there apparently is room for deviations in terms of friction and loose snow without significantly affecting the gait pattern also strengthens GsB as a good winter operation alternative. The major changes in terms of travel times and energy consumption occur when the surface is ice-covered, but no friction-increasing measures have been implemented. In such cases, one can expect increased travel times in the order of 1 min/km and approximately 5 % increased energy consumption compared to GsB.

If the rates of close calls found on the various pavement surface conditions presented in Table 5 are compared, it is seen that the RCC increased from 0.44 % to 2.94 % from GsB to gritted ice. Given that RCC is a valid indirect measure for accident risk, the findings from this study suggest the risk of single accidents to be approximately seven times greater on gritted ice than on optimal GsB. Similarly, if an ice surface is not gritted or no other friction-increasing measures are implemented, the risk of single accidents is approximately 14 times greater than on GsB. Seen from another perspective, gritting an ice-covered pavement reduces the single accident risk by half compared to not gritting it, assuming that the RCC is a valid indirect measure of single accident risk. However, these figures must be interpreted with care, considering they are based on a dataset with relatively few close calls. Based on the single accident study results and using close calls as an indirect measure, it seems like small deviations in terms of slipperiness from the optimal GsB are associated with substantial increases in single accidents. Therefore, whether GsB can be considered an equally good alternative as GsA depends on how well ice-formation can be prevented. If ice is present on the pavement, gritting the pavement will likely reduce the accident risks, but the accident risks still seem to be substantially higher than on an optimal GsB.

Assessing how easy it is to maintain an optimal GsB or GsA during a winter season has been out of the scope of the current research. However, this is a vital issue to determine when evaluating whether to supply either one. Karlsson (2021) reports that the main challenge on sections operated as GsA is related to weather changes when rain turns to ice and on sections operated as GsB when ice and snow soles dissolve. This indicates that ice prevention can be difficult on GsA as well.

4.3 Perceptions and behavioral adaptations

As shown in Paper I, partly ice-covered surfaces did not result in changes in route choice, which should be expected given that snow- and slush-covered surfaces caused significant changes in route choices. There are two plausible main explanations for this finding. One, the pedestrians did not perceive the difference between the sides as Side GsB was partially covered with ice. A thin layer of ice on GsB might manifest "invisibly" and thus resemble the asphalt pavement of Side GsA. Two, perhaps most pedestrians reasoned that they were willing to take the risk of maneuvering around the icy areas. Given that the first explanation is correct, it shows the importance of correspondence between what one perceives and the actual pavement surface conditions. Perhaps people were "tricked" into thinking they were walking on asphalt when they were actually walking on ice.

Seen in the context of the results from Paper II and Paper III, such a finding seems more problematic than it may have initially seemed. As shown in these studies, behavioral adaptations take place since pedestrians change their behavior when walking on actual slippery pavements that likely were perceived as such as well. They walk with shorter steps and reduce their speed. This results in more stable and safe walking while giving them more time to perceive the pavement surface conditions and make tactical assessments and operational adjustments. On the other hand, when walking on an asphalt pavement or GsA, these adjustments are not made to the same extent. On asphalt and GsA, pedestrians walk faster and with longer steps which, in contrast, is less stable and gives them a shorter time to perceive the pavement surface conditions. Based on this, it is reasonable to assume that if pedestrians walk on ice-covered pavements as if they walked on asphalt, the risk of single accidents will be higher than when walking on ice-covered pavements in the manner they would do when they perceive the pavements as slippery.

The actual single accidents reported in Paper IV further emphasize this point. All the single accidents occurred on seemingly good pavement surface conditions, but where particularly slippery spots were hidden or appeared abruptly. Therefore, it is reasonable to believe that a general improvement of the pavement surface conditions will not result in the expected reduction in single accidents in situations where the pavement surface conditions are not optimal but perceived as such because pedestrians will make behavioral adaptations and walk more carelessly. In order to avoid such unfortunate behavioral adaptation, it is very important that pedestrians perceive the pavement surface conditions as they actually are so that they can adapt adequately. However, this does not mean that a general improvement of the pavement surface conditions will not reduce the number of single accidents, but only that the effect will likely be lower than expected if behavioral adaptations are not taken into account. A Swedish study can perhaps be interpreted to support this claim. It shows that the single accident risk during winter depends on how often snow and ice are present on the pavements. When snow- and ice-covered pavements are less frequent, the accident risk increase in situations where snow- and ice-covered pavements are present, especially on the types of pavement surface conditions that basically have the highest accident risks (Niska, 2006; Høye et al., 2012).

In summary, a very important success criterion to prevent single accidents during winter seems to be to ensure correspondence between actual and perceived pavement surface conditions.

4.4 How suitable are close calls as an indirect measure of single accidents?

One of the research objectives of Paper IV was to evaluate whether using close calls as an indirect measure of single accidents is appropriate for studying single accidents among pedestrians during winter. The main precondition for such a method to be applicable and valid is a causal relationship between single accidents and close calls. The assumption is that the relative difference between single accidents and close calls on different pavement surface conditions is equal and proportional. If this is true, it is more appropriate to collect data on close calls on various winter pavements because it must be assumed that they occur far more often than single accidents. The time spent on data collection can then be reduced. In order to be able to verify whether there is a causal connection, enough data on both single accidents and close calls on different types of winter pavements must be obtained. In the conducted study, not enough data was collected to verify or disprove such a causal relationship.

Some data was collected on single accidents. As shown, all single accidents occurred on heterogeneous pavement surface conditions. In the study's research design, a prerequisite was that the close calls had to occur between the start and end points shown in Figure 5 to be able to control for exposure. Between these two points, the pavement surface conditions were always homogeneous. This differentiation means that the collected data on single accidents and close calls are not directly comparable. However, the data on single accidents provide useful information. If most single accidents during winter occur on heterogeneous conditions, it is not as interesting to collect data on close calls on homogeneous conditions. If most single accidents occur on heterogeneous conditions, a probable cause for this is behavioral adaptations based on misperceptions of the pavements, as discussed in Section 4.3. Pedestrians who walk on ice and slippery snow walk more stably and slower and are likely better mentally prepared to make maneuvers and avoid falling if they slip and are about to fall.

4.5 Identified areas for future research

Through the conducted research and based on the existing literature, some important knowledge gaps that should be the topic of future research have been identified.

First, if a similar approach as used in Paper IV is regarded useful, more data is needed on single accidents or close calls to get valid estimates of the accident risks associated with various pavement surface conditions during winter. This is especially important to enable reliable cost-benefit analyses of winter operational measures, as discussed in Paper III.

Second, in relation to the first point, effects on induced demand by winter operational measures are needed. Previous research has shown that improved winter operations can increase bicycle traffic and decrease car traffic (Bergström and Magnusson, 2003). Similar studies on the potential to increase pedestrian traffic during winter have not been identified. However, previous research has shown that older pedestrians are especially reluctant to walk outdoors when it is slippery due to ice and snow (Shumway-Cook et al., 2003; Johansson and Bjørnskau, 2020). Whether the general population will drive less and walk more if the pavement surface conditions in winter, in general, were improved must be investigated further. It will also be of interest to identify what LOS will make people walk more during winter. Is it necessary to supply more GsA, or will supplying GsB be sufficient to increase the share of walking? The effects on induced demand will also be essential input data in cost-benefit analyses.

Third, as partly discussed in Section 4.1, relationships between pavement surface conditions and walking for groups of pedestrians that are likely more negatively affected by sub-optimal conditions are needed. In this regard, replications of the conducted studies investigating older pedestrians using walkers, pedestrians that are either visually or physically impaired, wheelchair users, and others that for some reason might have higher thresholds for when the pavement surface conditions are acceptable, are interesting. Studies investigating these groups of pedestrians but focusing on other aspects of walking like trip production and mode choices during winter will also be valuable and useful contributions to the literature.

5.0 Conclusions

This work has demonstrated some relationships between pavement surface conditions during winter and pedestrians' walking behavior. Pavement surface conditions have a significant impact on pedestrians' route choices. Specifically, pedestrians state that they often make different route choices in winter than in summer, and these decisions are most often made to avoid slippery surfaces. When GsA is available, some pedestrians change their route from GsB to walk on GsA, even when the amount of snow or slush is minimal on GsB. On the other hand, a surface partly covered with (partly invisible) ice did not deter pedestrians from choosing Side GsB, indicating that correspondence between actual surface conditions and pedestrians' visual perceptions is an important factor in their informed decision making.

Step lengths are significantly reduced on snow- and ice-covered surfaces compared to GsA, and step frequencies are significantly increased on ice compared to GsA. These changes in walking behavior are likely activated to increase stability and reduce the risk of falling on slippery surfaces. However, one effect of these alterations in walking behavior is that the energy consumption of walking is increased. It is plausible that this increases exhaustion, is deemed less attractive, and likely reduces acceptable walking distances on sub-optimal conditions during winter.

There is a significant relationship between pavement surface conditions and average walking speeds. When comparing GsA to optimal GsB, the average travel times are expected to be 1 min/km longer on the latter than the former. On clean ice, compared to GsA, the expected travel times are 2 min/km longer.

On homogeneous pavement surface conditions, given that close calls can be used as an indirect measure of single accidents, the single accident risk on gritted ice is approximately seven times greater, and on clean ice, 14 times greater than on optimal GsB. Hence, the risk of single accidents can be halved by gritting an ice-covered pavement. Further, seemingly good pavement surface conditions, where particularly slippery spots are hidden or appear abruptly, are suggested to be a likely cause of many single accidents during winter. However, the method used has some limitations that must be addressed in future research.

When the different studies are seen in relation to each other and the existing literature, it does not seem to matter much for an individual pedestrian whether GsA or GsB is supplied, given that both keep a standard as intended. However, considering wheelchair users, physically or visually impaired people, and older people using walkers for mobility might alter this conclusion. The major negative impact in terms of speed reduction appears on pavements with clean ice. Given that RCC is a valid indirect measure for accident risk, single accidents risks, on the other hand, seem to be more sensitive to varying pavement surface conditions. They seem to increase substantially as the slipperiness of the pavement increases even when friction increasing measures like gritting is implemented compared to the expected accident risks on GsB with high available friction and GsA. In terms of single accidents, it seems like a critical success criterion to prevent single accidents during winter is to ensure correspondence between how the pedestrians perceive the pavement surface conditions and how they actually are.

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A Paper I

Pedestrians’ and bicyclists’ route choice during winter conditions

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Pedestrians’ and bicyclists’ route choice during winter conditions

This study investigates the association between surface conditions and pedestrians’ and bicyclists’ route choices during winter. We analyzed responses from two surveys in which pedestrians and bicyclists answered questions regarding their route choices in winter environments. We also conducted an experimental study to investigate the association between surface conditions and route choice. The results indicate that surface conditions have a significant impact on pedestrians’ and bicyclists’ route choice. Specifically, pedestrians avoid slippery surfaces in general, while bicyclists avoid surfaces with a build-up of loose snow on the pavement. When bare pavement is available, some pedestrians change their route from snow- or slush-covered surfaces to walk on a bare surface, even when the amount of snow or slush is minimal. On the other hand, based on the experimental results, a partly ice-covered surface did not deter pedestrians, indicating that a correspondence between actual surface conditions and pedestrians’ visual perceptions is an important factor in their informed decision making. Decision makers can use the results to gain an understanding of which winter maintenance measures are the most important for implementation in order to provide an acceptable service level that promotes walking and cycling in a winter environment.

Keywords: route choice; pedestrian; cyclist; winter operation and maintenance; surface condition

1.0 Introduction

Today, governments and transportation planners in many places are encouraging people to walk and cycle more, as active mobility offers several benefits compared to driving a car, including health gains, reduced emissions, less congestion, and reduced road maintenance costs. Understanding road user behavior is essential for implementing the most efficient measures to make walking and cycling more attractive.

In cold regions, weather conditions can vary substantially by season. These weather differences affect streets and roads. In winter, snowfall and freezing and thawing result in snow and ice buildup on the pavement. This can be a real challenge that must be overcome to supply infrastructure that supports an acceptable level of accessibility for all road users.

To cope with these problems, certain levels of winter operation and maintenance are usually required. Snow removal by plowing or scraping, friction-increasing measures such as sanding or gritting, and some anti- and de-icing applications are typical examples of winter operations conducted on a day-to-day basis to support safe, efficient travel.

A critical aspect of road user behavior is route choice. Route choice is especially interesting because, more so than whether to go on the trip at all, mode choice, and when to travel, it is typically the first road user travel behavior that changes when pedestrians and bicyclists perceive compromised safety (Backer-Grøndahl et al., 2007). Given that slippery or otherwise difficult to maneuver surfaces are typically associated with compromised safety, this is a good starting point for investigating which types of surfaces pedestrians and bicyclists find more or less attractive.

Although extensive research has been conducted on pedestrians' and bicyclists' route choices, the association between route choice and surface conditions during winter has not yet been thoroughly studied. This study's research questions were as follows:

(1) How do pavement surface conditions affect route choice decisions during winter?

(2) Does a difference in winter maintenance service level––that is, between a bare pavement standard and a winter pavement standard––affect pedestrians' and bicyclists' route choices?

We examine both pedestrians and bicyclists in this paper rather than investigating them independently in separate papers because they usually share the same road or street facilities. In Norway, where this study was conducted, bicyclists are allowed to use sidewalks. Even when the two groups are separated, the methods used to operate and maintain the facilities they use are usually the same.

2.0 Literature review

Unlike vehicular traffic, where route choice is mainly based on efficiency, several factors influence pedestrians' and bicyclists' decisions.

2.1 General factors that influence pedestrians' route choice

The literature suggests that pedestrians choose routes with which they feel comfortable. When they perceive their current route as unattractive, they take detours to utilize more comfortable routes (Corazza et al., 2016; Marisamynathan and Vedagiri, 2014; Ren et al., 2011). After conducting on-site interviews in six European cities to explore aspects of pedestrian comfort, Øvstedal and Ryeng (2002) found that pedestrians' feelings of safety and security are the most important factors when walking outdoors. Feeling safe and secure and surface quality were found to be the most important factors influencing pedestrians' sense of comfort.

In general, when several route options are available, pedestrians tend to choose the shortest route to reach their destination (Verlander and Heydecker, 1997; Seneviratne and Morrall, 1985; Muraleetharan et al., 2005). Other factors influencing route choice are the width of the walkway, pavement surface characteristics, attractions along the route, the purpose of the trip, conflicts with other road users, and available facilities (Muraleetharan et al., 2005). Pedestrians state that they sometimes choose a different route because of compromised safety. Based on surveys in two Norwegian cities, Backer-Grøndahl et al. (2007) found that 60% of pedestrians sometimes chose a different route because they felt unsafe, and 7% did so often. Pedestrians feel more unsafe in the evening than during the daytime. Insufficient street lighting, the fear of encountering unpleasant people, and other road users' behavior were found to be more important than surface conditions in making pedestrians feel unsafe.

2.2 Winter-related factors that influence pedestrians' route choice

Of the general factors that influence pedestrian route choice, the quality of the surface is directly related to winter operation and maintenance. In winter, the pavement surface is affected by the chosen winter maintenance level of service (LOS) and how well it is executed. In particular, the evenness of the pavement, friction level, and accessibility were affected by winter maintenance. Walkway width can also be affected by winter maintenance through the effectiveness and rationality of snow clearance and storage. In a Swedish study based on interviews and observations, Sakshaug et al. (2013) found that very few people make detours to walk on bare instead of icy road surfaces. They concluded that many people do not seem to take the risk of slipping and falling seriously.

2.3 General factors that influence bicyclists' route choice

Bicyclists' route choices are sensitive to the effects of distance, slope, the presence or absence of traffic lights, traffic volumes, and turn frequency (Broach et al., 2012; Stinson and Bhat, 2003). Travel time is another important factor in bicycle route choice, especially for commuters (Sener et al., 2009). Wardman et al. (2007) found that time spent cycling is valued approximately three times higher than travel times for other modes. Furthermore, bicyclists prefer simple routes and want to travel in straight directions (Zimmermann et al., 2017).

The presence and quality of infrastructure are also key factors in their route choice. A recent study from Oslo, Norway found that, on average, bicyclists cycle 21% longer than the shortest possible route (Hulleberg et al., 2018). Detours are mainly made to access cycling infrastructure that is separated from other traffic. Avoiding upward slopes was found to be another important factor influencing route choice decisions. Menghini et al. (2010) found that distance was the most important variable influencing bicyclists' route choices in Zürich, Switzerland. The portion of bicycle paths was also found to be substantial, but this had a smaller impact than distance.

Backer-Grøndahl et al. (2007) found that 55% of bicyclists sometimes changed their travel route because they felt unsafe; however, only 1% reported doing this often. For bicyclists, surface conditions and other road users' behavior were found to be the main reasons contributing to their sense of compromised safety (Backer-Grøndahl et al., 2007).

2.4 Winter-related factors that influence bicyclists' route choice

Most research related to bicycling in winter conditions has investigated how winter-related variables affect the decision of whether to cycle, without specifically examining route choice. In a survey of 1 402 current and potential cyclists in Vancouver, Canada, Winters et al. (2011) found that snowy and icy routes were major deterrents when deciding to ride a bike. In a study of the self-reported commuting trips of bicyclists from a northern US state, Flynn et al. (2012) found that approximately 2.5 cm of snow on the ground reduced the likelihood of cycling by about 10%. Better snow clearance and perhaps ice formation prevention could lead to a higher winter cycling rate. Indeed, in a Swedish study, Bergström and Magnusson (2003) found that improving winter maintenance has the potential to increase the number of winter bicycle trips by 18%. Snow clearance was found to be the most important measure for achieving this.

Although many studies have investigated the effects of pedestrian and bicycle route choices, there is obviously a knowledge gap in the association between surface conditions during winter and pedestrians' and bicyclists' route choices.

2.5 Winter maintenance levels of service

The desired objective of winter operation and maintenance is to create acceptable surface conditions. The goal is to maintain, restore, control, or improve surface conditions to a level that acceptably supports safe, effective travel. In this paper, we will distinguish between two winter maintenance LOS: GsA and GsB.

GsA is basically the implementation of a bare-road strategy for pedestrian and bicycle facilities. Salt is usually used for anti- and de-icing to keep the pavement free of snow and ice. For snow clearance, the pavement is swept by a vehicle with a front-mounted power broom in a manner similar to Swedish "sweep-salting." There are indications that this method results in an increased number of winter bicycle trips and reduced incidence of accidents caused by skidding; in addition, bicyclists, in general, are pleased with the results (Niska and Blomqvist, 2016; Niska and Blomqvist, 2019, Niska et al., 2019).

On the other hand, GsB is the implementation of a winter road strategy for pedestrian and bicycle facilities. Snow is cleared by plowing, and salt is usually not used for anti- and de-icing. Instead, sanding or gritting is used as a friction-increasing method if the pavement becomes slippery owing to compaction and freezing. GsB also has several requirements regarding the evenness of the pavement, the friction level, and the height of loose snow. The snow accumulated on the pavement should be compact, not loose.

Ideally, the use of salt should be minimized. However, salting for anti-icing, de-icing, and anti-compaction purposes is widespread in Norway. It is a popular method used on roadways, especially in regions where the temperature fluctuates around 0 °C and traffic volume is high. In 2017/18, 325.000 tons of salt were used on Norwegian roads (Statens vegvesen, 2019). In recent years, an increased portion of Norwegian pedestrian and bicycle facilities have also been salted owing to the prioritization of these modes of transport. It is assumed that both bicyclists and pedestrians prefer black instead of white pavement, with a compact layer of snow on the asphalt. The use of salt has often been criticized because of environmental concerns and the fact that salt corrodes infrastructure, vehicles, and bikes.

3.0 Methods

3.1 Surveys

Two surveys asking respondents a wide range of questions concerning winter operations and maintenance were administered to answer the first research question. The surveys were created and distributed by the Institute of Transport Economics, Norway. Only the excerpts concerning route choices are presented here. The remainder has been published separately (Johansson and Bjørnskau, 2020a; Johansson and Bjørnskau, 2020b; Aasvik and Bjørnskau, 2021).

The first survey targeted pedestrians and was distributed in February 2019. The second targeted bicyclists and was distributed in June 2019. The two surveys were distributed at different times because they were administered as part of two independent studies. However, since the questions analyzed in this paper are identical in both, we treat them as if they were conducted as part of a single study. The survey was web-based. A total of 2,745 respondents answered the online pedestrian questionnaire. The respondents included members of the Norwegian Automobile Association (n = 1628), the Norwegian Association of Disabled (n = 7), and the Norwegian Pensioners' Association (n = 31), as well as persons who signed up for an e-mail list (n = 1079). Members of the Norwegian Automobile Association make up 59% of the sample. Respondents from this group were included because they were convenient to recruit, since their member register was available to the Institute of Transport Economics, which distributed the survey. Their members make up 9% of the population in which the study was conducted. Approximately 70% of the population had a driver's license and an available car at most times, and most drivers were also pedestrians. Therefore, we argue that increasing the sample size by including this group is a greater gain for the study than the potentially negative effect this group could have on the sample's representativeness.

For the bicycle survey, respondents were recruited from e-mail lists (n = 87) and using posters at bicycle workshops (n = 35). In addition, employees in the city of Oslo received an e-mail invitation (n = 846), and respondents were drawn from the Norwegian Cyclists' Association (n = 566), as well as through invitations sent via cycling-themed Facebook groups and those generally consisting of dedicated cyclists (n = 885). Other respondents received a link to the survey from project partners in the Norwegian Public Roads Administration (n = 137). This sampling method can be categorized as convenience sampling. It was made clear to the invitation recipients that the target group was cyclists. The survey was web-based, and there were 2,556 respondents in total.

As previously mentioned, the questions analyzed in this study are identical in both surveys. Both surveys' respondents were asked questions regarding their daily travel behaviors, their attitudes to operation and maintenance related to their travel behavior, and their background information such as age, gender, and place of residence. Respondents were asked about their general travel behavior during winter and not about a specific trip. The questions were formulated to cope with the time lapse between the bicycle survey's spring/summer distribution and the survey content requesting the report of typical behavior during winter. Information about trip purpose was not retrieved from either survey.

Filtering was performed to analyze typical pedestrians and bicyclists who are familiar with winter conditions. For the pedestrian survey, only respondents who reported that they usually walk outside during winter and that they leave their homes at least 4–5 times per week were included in the analyses. For the bicycle survey, only bicyclists who stated that they often cycle during winter were included.

For both surveys, we also performed filtering based on the respondents' place of residence. We filtered out those who live in western and southern Norway, where there is little snow and the average winter temperature is above 0 ºC, and retained the respondents from the eastern and northern parts. After filtering, there were 1 677 pedestrian survey respondents and 736 bicycle survey respondents. Data were analyzed using SPSS Statistics 26.

3.2 Limitations of the surveys

Due to the recruitment methods used, we do not know the response rates, and we cannot conclude whether the samples represent the overall population. In particular, the bicycle survey, where many respondents are members of the Norwegian Cyclists' Association, is likely not representative of the average Norwegian bicyclist. However, we are only interested in those who actually walk or cycle during winter and those who are familiar with walking and cycling in such conditions. This is because we want to analyze actual and not potential behavior as much as possible. Therefore, the results reflect experienced winter cyclists' and pedestrians' behavior, not that of inexperienced and potential pedestrians and bicyclists. The results should be evaluated with this in mind.

Since the surveys are based on self-reported behavior, the results will be affected by any bias resulting from self-reporting. More specifically, the survey targeting bicyclists relies on self-reported winter behavior reported approximately six months after the end of the winter season. Since the bicycle survey sample mainly consists of experienced winter cyclists, it is assumed that any bias or error resulting from this is minor.

3.3 Experimental study

We conducted an experiment to answer the second research question. The experiment quantified pedestrian and bicycle traffic on two identical pedestrian and bicycle facilities separated by a roadway (see Figure 1). Traffic was quantified in the fall when the surface conditions were identical on both sides; this was the reference period. During winter, one side was maintained through GsA by using salt for anti-icing, de-icing, and anti-compaction, and sweeping for snow clearance. This resulted in a bare pavement surface with visible black asphalt during the entire period.

The other side was maintained through GsB by plowing for snow clearance without the use of salt. In practice, this means that we allowed a compact or loose layer of snow to accumulate on the asphalt, depending on the amount of snow. When needed, gravel was used as a friction-increasing measure for GsB. In winter, the temperature fluctuated around 0 °C. This resulted in Side GsB, where no salt was used to create varying surface conditions depending on weather and temperature. The surface conditions on this side varied between snow-, slush-, and ice-covered pavement. The amount of snow, slush, and ice on the GsB was relatively modest owing to the weather during the observation period. During this period, the snow depth on the surface was 5 cm or less. Typical examples of the surface conditions of GsB during winter are shown in Figure 2.

Data collection was conducted in fall 2018 and winter 2019. The infrastructure where the observations were obtained was identical in both periods. Traffic was quantified on five random weekdays in fall and seven weekdays in winter. Observations were taken between 07:30 and 18:00. The data consist of 2 060 observations of pedestrians, with 1 246 in fall and 814 in winter. From a total of 1,292, the number of bicycle observations in fall was 965, and in winter, the number of observations was 327.

All observations were taken manually, on-site. The pedestrians and bicyclists were unaware of their registration. They were not informed that the two sides were maintained differently during the winter; they had to ascertain that through experience or visual perception. The pedestrians and bicyclists were categorized according to gender, travel direction, and age (over or below approximately 60 years of age based on observation). The time of day was registered and divided into morning rush, midday, and evening rush.

The experimental site was a suburban street in Trondheim, Norway. The street lies in a shopping area, and most traffic at the site is either commuter or shopping traffic. This site was selected because pedestrian and bicyclist facilities are identical on each side of the roadway separating them. The annual average daily traffic (AADT) on the roadway was approximately 15 300 vehicles/day. The only varying factors between the two sides are different stores and other destination points along the walkways and cycleways, and the difference in winter maintenance LOS during the winter period. The roadway is relatively flat, with an incline of approximately 0.9%. A schematic of the experimental site is shown in Figure 1.

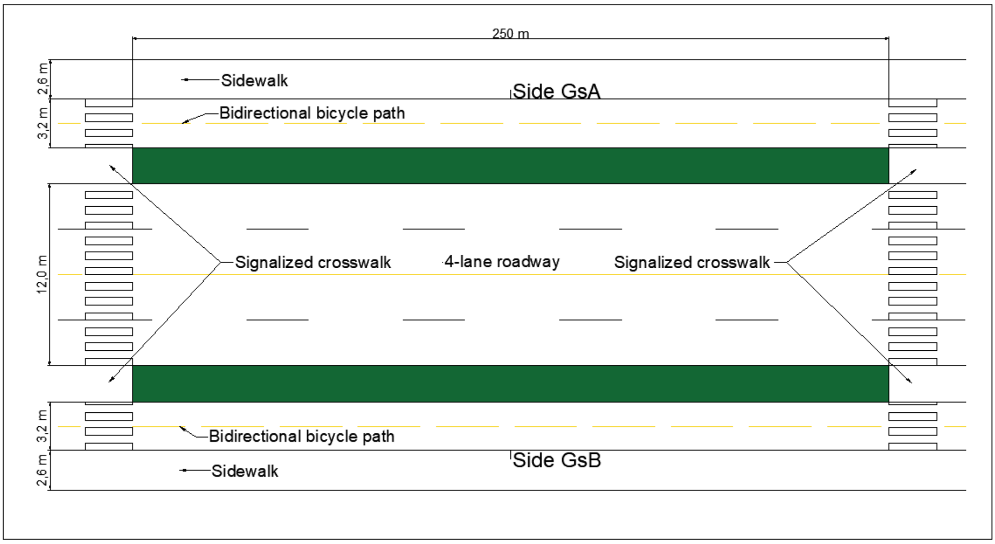

Figure 1 Sketch of the experimental site.

Of course, route or side choice is affected by trip origin and destination. To reduce this effect, we required that for any trip to be registered and form part of the dataset, the pedestrian or cyclist had to walk or cycle at least 250 m between the two crosswalks, as illustrated in Figure 1. This criterion was included to ensure that the pedestrian or bicyclist had a choice regarding whether to cross the street at either end of the registration area and therefore had at least one opportunity to choose the alternative side instead. Further, we assumed that if a trip started or ended between the crosswalks, there was no choice involved, and the side where the trip started or ended would always have been chosen. Therefore, we did not register the trips that started or ended between the crosswalks; we only included those trips that spanned both crosswalks, as illustrated in Figure 1. In practice, the pedestrian or cyclist had to pass both crosswalks, pass one and cross the other, or cross both. The goal was to capture the pedestrian and bicyclist thru traffic because it was assumed that these road users have greater side choice freedom than those we excluded from the dataset. The crosswalks are signalized and actuated by pushing a button. The waiting time for a green signal to cross the roadway varies between 20 seconds and 60 seconds, depending on traffic volume.

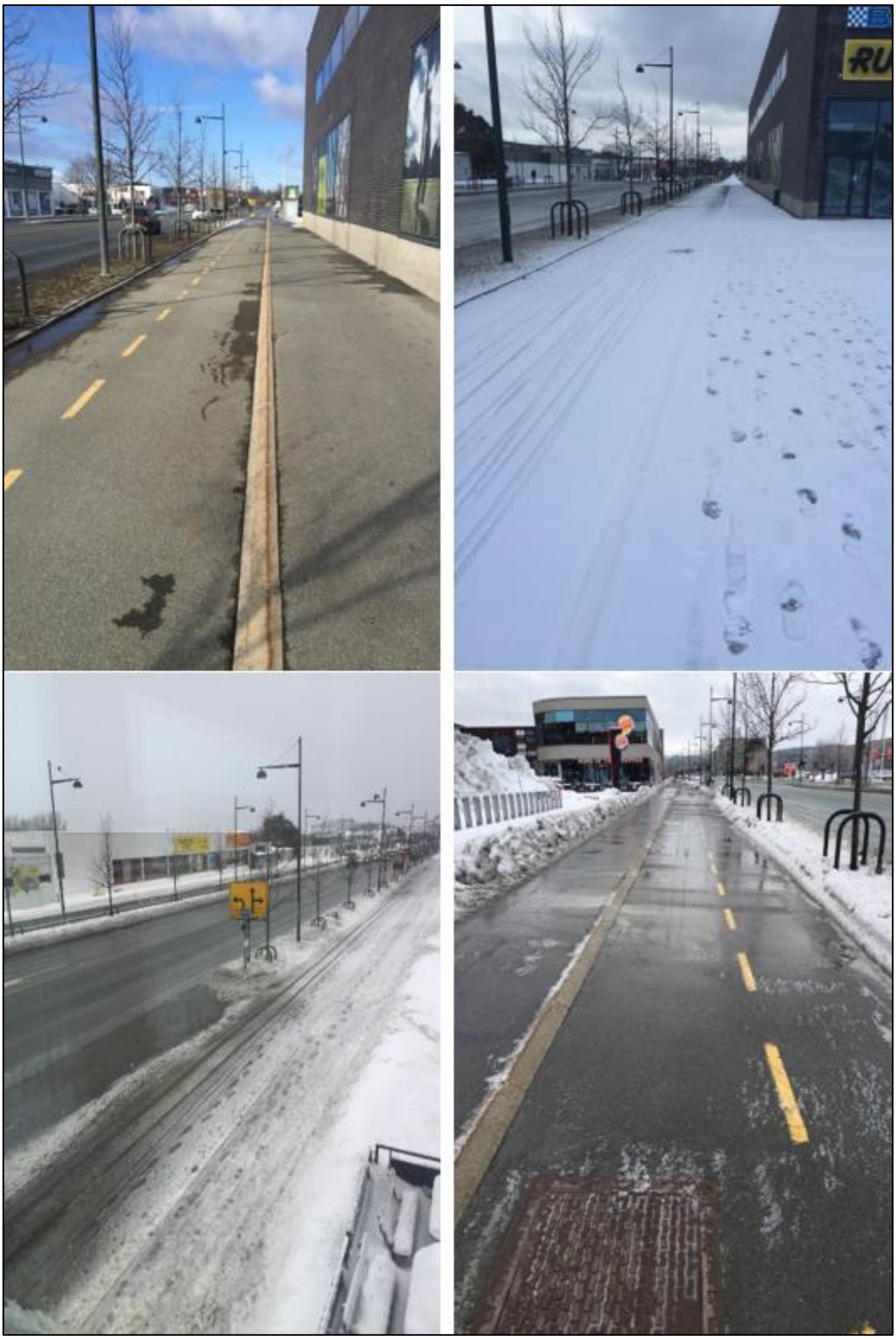

Figure 2 Typical examples of the categorized surface conditions. Top left: Bare pavement. Top right: Snow-covered pavement. Bottom left: Slush-covered pavement. Bottom right: Partly ice-covered pavement.

3.3.1 Analyses

The data were analyzed using Stata version 16. We analyzed the data using binary logistic regression because the outcome variable was binary: The pedestrian or bicyclist walks/cycles on either Side GsA or Side GsB. At the time of registration, each pedestrian or bicyclist that satisfied the criterion outlined in Section 3.3 was registered as walking/cycling on either Side GsA or Side GsB.

The main explanatory variable of interest was surface condition. The reference category for this variable, to which the other categories are compared, was when Side GsB had an uncovered asphalt surface. At that time, the surface conditions on Sides GsA and GsB were identical. This occurred during fall. During winter, the surface condition on Side GsB was either snow, slush, or partly ice covered. Each condition was coded separately. Side GsA always had an uncovered asphalt surface at registration. In summary, the surface condition variable has four categories, one for each of the surface conditions present on Side GsB at some point.

The data were collected during fall when both sides had the same surface conditions to provide a reference for comparison. It was assumed that the number of pedestrians and bicyclists usually walking/cycling on Sides GsA and GsB, respectively, would not be split 50/50 but would be skewed to one side or the other due to factors not controlled for in the regression models. Such factors were assumed to be, for instance, placement of different stores, placement of bus stops, general work trip origins/destinations in the area, and other similar reasons. If data were only collected during winter when the two sides' surface conditions differed, it would not have been possible to determine how the surface conditions affected the likelihood of choosing one side or the other because the "natural" skewness in the portion that usually uses either side would be unknown.

To test whether any predicted association between surface condition and route choice could be explained by the time of day when the observations were made or by travel direction, we included these variables in the regression models as control variables. We also included the variables of gender and age to determine whether these influenced the choice. All independent variables in the regression model were categorical.

Pedestrian and bicycle data were handled separately in the analyses. Model 1 predicts pedestrians' side choice, whereas Model 2 predicts bicyclists' side choice. For both analyses, we report the regression coefficients in log-odds units, standard errors, and *p*-values. Statistical significance was set at $P < 0.05$.

3.4 Limitations of the experimental study

A general remark on the experiment that is relevant to both bicyclists and pedestrians is that some road users might not have been aware that the two sides were maintained differently. If they were not aware of this difference, we would not expect the portion of pedestrians or cyclists to vary between the two data collection periods. One implication of this is that the result showing no difference in the portions of pedestrians and cyclists using the two sides in the two periods does not necessarily mean that surface conditions do not affect route choice. On the other hand, if the results show a difference, the effect size might be underestimated because many might not have been aware of the different surface conditions on the two sides.

4.0 Results

4.1 Surveys

4.1.1 Pedestrians

We analyzed 1 677 pedestrian survey respondents' answers. The sample consisted of 1 099 men and 578 women; 988 respondents were in the 20–60 age group, and 689 were in the 60–90 age group. Almost one quarter of the pedestrians always or very often use an anti-slip device such as a crampon when walking during winter.

Table 1 shows the number of people who chose alternative walking routes in winter compared to in summer. As shown in Table 1, 55.5% of pedestrians stated that they sometimes or very often chose different routes in winter compared to in summer. Of the pedestrians, 29.3% stated that they did not change their route in winter.

Table 1 Question asked: Do you choose to walk other routes in winter compared to in summer?

	All (%)	Men (%)	Women (%)	< 60 years old (%)	> 60 years old (%)
Yes, very often	22.2	20.5	25.6	20.3	25.0
Yes, sometimes	33.3	32.3	38.2	33.5	35.6
Yes, but seldom	14.1	15.0	12.3	13.4	15.1
No	29.3	32.2	23.9	32.8	24.4
N	1 677	1 099	578	988	689

In general, women are more likely than men to choose alternative routes when walking in winter compared to summer. Those above age 60 are more likely than those below age 60 to choose alternative routes.

Table 2 shows that the main reason pedestrians change their travel route is due to slipperiness owing to the presence of ice and snow. More than half (58.3%) of the respondents stated this as a reason for their choice. Many (37.5%) reported that another reason for changing travel route is that it is laborious to walk in snow. Uneven surfaces are the third most common reason for choosing alternative routes in winter conditions (10.1%). Older pedestrians are more likely than younger pedestrians to choose alternative routes because of slippery surfaces. Women are more likely than men to choose alternative routes for the same reason.

Table 2 Reported reasons pedestrians chose alternative routes in winter conditions. The respondents could select multiple reasons and add reasons not given as answer options.

Because…	All (%)	Men (%)	Women (%)	< 60 years old (%)	> 60 years old (%)
it's laborious to walk due to snow.	37.5	35.6	41.2	39.7	34.4
it's slippery due to ice/snow.	58.3	54.1	66.3	55.0	63.1
of inadequate lighting.	8.2	6.0	12.5	9.9	5.8
of uneven road surfaces.	10.1	8.6	13.0	9.6	10.7
of local air pollution.	3.5	3.0	4.5	3.6	3.3
of conflicts with other road users.	5.6	6.0	4.8	5.8	5.4
I am uncertain if it is plowed and/or sanded.*	-	-	-	-	-
other reasons.	5.1	4.8	5.5	4.1	6.4
N	1 677	1 099	578	988	689

*This option was only included in the bicycle survey; it did not appear in the pedestrian survey.

4.1.2 Bicyclists

We analyzed 736 bicycle survey respondents' answers. The sample consisted of 486 men and 250 women; 622 respondents were in the 20–60 age group, and 113 were in the 60–90 age group. In the sample, 96.2% of bicyclists always or usually used studded tires when cycling during winter.

Table 3 shows the number of people who chose to cycle on other routes in winter compared to in summer. As shown, 48.6 % stated that they sometimes or very often chose different routes in winter than they would in summer.

Table 3 Question asked: Do you choose to cycle other routes in winter compared to in summer?

	All (%)	Men (%)	Women (%)	< 60 years old (%)	> 60 years old (%)
Yes, very often	16.3	15.0	18.8	17.0	12.4
Yes, sometimes	32.3	32.1	32.8	32.5	31.0
Yes, but seldom	14.5	15.8	12.0	14.0	17.7
No	36.8	37.0	36.4	36.5	38.9
N	736	486	250	622	113

Approximately one third (36.8%) of the bicyclists stated that they never changed their route in winter compared to in summer. From Table 4, we see that the most stated reason for choosing an alternative route is that it is laborious to cycle in snow. Half (49.9%) of the bicyclists stated this. The second most common reason for choosing alternative routes is that uncertainty as to whether the routes were plowed and/or sanded (33.3%). The third most common reason is because of slippery surfaces (17.9%). Almost one quarter of the female bicyclists changed routes due to slippery surfaces; 14.4% of the males in the sample exhibited the same behavior. Slipperiness due to ice and snow is the condition for which male and female bicyclists deviate the most in their answers. In general, bicyclists are more concerned than pedestrians about conflicts with other road users in winter, and 14.8 % of bicyclists change their travel route for this reason.

Table 4 Reported reasons for bicyclists to choose alternative routes in winter conditions. The respondents could select multiple reasons and add reasons not given as answer options.

Because…	All (%)	Men (%)	Women (%)	< 60 years old (%)	> 60 years old (%)
it's laborious to cycle due to snow.	49.9	48.4	52.8	51.0	44.2
it's slippery due to ice/snow.	17.9	14.4	24.8	18.0	17.7
of inadequate lighting.	2.7	1.2	5.6	3.1	0.9
of uneven road surfaces.	13.7	11.3	18.4	14.5	9.7
of local air pollution.	7.5	8.4	5.6	7.9	5.3
of conflicts with other road users.	14.8	15.4	13.6	15.9	8.8
I am uncertain if it is plowed and/or sanded.	33.3	30.2	39.2	34.4	27.4
Other reasons.	9.9	9.9	10.0	9.3	13.3
N	736	486	250	622	113

The respondents were also shown pictures of a snow-, slush-, and ice-covered road surface (see Table 5) and asked how often they chose another route when the conditions were as shown in the pictures.

Table 5 Question asked: How often do you choose an alternative route when the surface conditions are as shown in the pictures?

					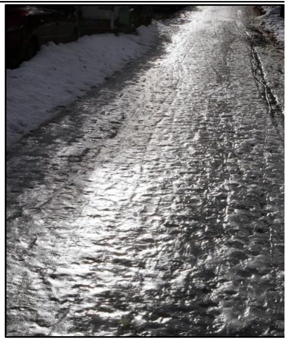	
	Snow-covered		Slush-covered		Ice-covered	
	Pedestrians (%)	Bicyclists (%)	Pedestrians (%)	Bicyclists (%)	Pedestrians (%)	Bicyclists (%)
1 Never	26.6	6.8	15.2	11.0	7.2	21.3
2	22.3	10.7	21.4	18.8	14.9	24.9
3	18.6	11.4	23.4	18.5	18.2	16.2
4	16.3	19.9	19.3	19.7	21.8	16.9
5 Very often	13.6	50.8	18.0	29.4	35.0	19.9
6 Don’t know/ not relevant	2.7	0.3	2.8	2.5	2.9	0.7
N	1 626	717	1 474	670	1 644	727

Table 5 shows a clear difference between pedestrians’ and bicyclists’ preferences. A loose snow layer on the pavement is the condition that deters bicyclists the most, while this is less so for pedestrians. On the other hand, a frozen layer of ice on the pavement is the condition that deters pedestrians the most, but for bicyclists, this is less problematic than the other surface conditions. The reason ice is less of a deterrent for bicyclists is most likely because almost all of them use studded tires during winter. Slush is more of a deterrent than loose snow for pedestrians and more of a deterrent than ice for bicyclists.

4.2 Experimental study

The regression models for pedestrians and bicyclists are presented in Table 6. Model 1 predicted pedestrians’ reduced usage of Side GsB, and hence, their increased use of side GsA – when the GsB surface was covered with snow and slush, as illustrated in Figure 2, compared to when it was bare in the reference period. When the GsB surface was partly covered with ice, the model predicted no change in its usage. Age was found to influence side choice. The model predicted that those above approximately 60 years old would be more likely to choose GsB than those younger than age 60. The time of day also affects route choice in Model 1. There was reduced use of Side GsB at midday and during evening compared to morning. Model 2 shows that surface conditions do not affect bicyclists' route choice. The only significant variable in Model 2 is the time of day when the observations were taken, with an association similar to that found for pedestrians.

Table 6 Binary logistic regression models. Predicting pedestrians' (Model 1) and bicyclists' (Model 2) Side GsB usage.

	Model 1 Pedestrians	Model 2 Bicyclists
Surface: Asphalt (reference period)	0 (base)	0 (base)
Surface: Snow	-0.305* (0.14)	-0.177 (0.20)
Surface: Slush	-0.434** (0.14)	0.249 (0.23)
Surface: Ice	0.080 (0.16)	-0.064 (0.22)
Age: < 60 years old	0 (base)	0 (base)
Age: > 60 years old	0.398** (0.15)	-0.306 (0.49)
Gender: Women	0 (base)	0 (base)
Gender: Men	0.098 (0.09)	-0.094 (0.11)
Travel direction: East	0 (base)	0 (base)
Travel direction: West	-0.153 (0.09)	0.081 (0.11)
Time: Morning	0 (base)	0 (base)
Time: Midday	-0.636*** (0.13)	-0.729*** (0.15)
Time: Evening	-0.403**	-0.483**

	(0.15)	(0.15)
Constant	0.068	0.529***
	(0.14)	(0.15)
N	2 060	1 292

Coefficients are in log-odds units, and standard errors are in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Since the regression models' coefficients can be challenging to interpret, we converted the associations between surface conditions and pedestrians' route choice to probabilities. Figure 3 shows the average marginal effects of the association between surface condition and the portion of pedestrians walking on Side GsB. It shows the change in probability as a function of surface conditions when everything else is held constant. We can see that when snow was present on the walkway, the model predicted a seven percentage point decrease (95% confidence interval [CI] between 13 and 1 percentage point(s)) in the portion that used it compared to the reference period when it was bare. Similarly, when slush was present on the walkway, the model predicted a ten percentage point decrease (95% CI between 16 and 4 percentage points). There was no change in the number of pedestrians that used Side GsB compared to the reference period when ice was present on the surface. All 95% CIs are quite broad, which means that the actual effect is uncertain. However, our analysis shows that snow and slush on the walkway are deterrent factors for some pedestrians, which increases the probability that an alternative route with a bare surface will be used. Further, due to overlapping CIs, Figure 3 shows that we cannot determine whether slush on the surface is more of a deterrent than dry snow.

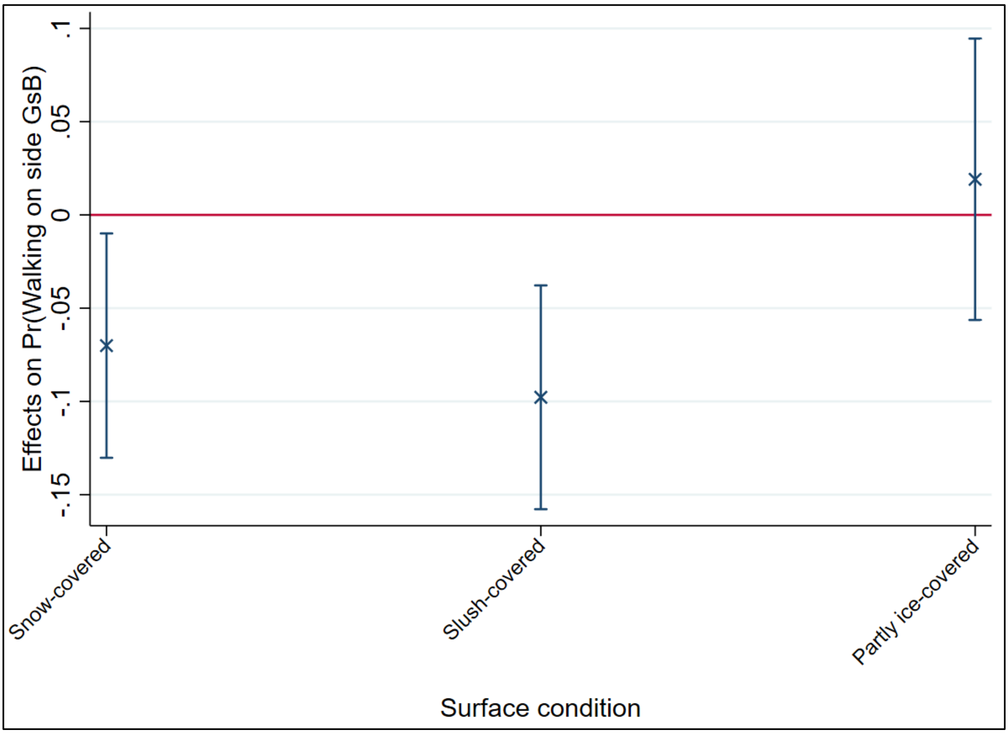

Figure 3 Average marginal effects with a 95% CI. It shows the discrete change in the number of pedestrians walking on Side GsB for the different surface conditions, compared to the base level, that is, the reference period when Sides GsB and GsA both had a bare asphalt surface.

5.0 Discussion

In this paper, we set out to address the research questions outlined in Section 1.0. We wanted to investigate whether surface conditions affect route choice decisions during winter and whether a difference in winter maintenance service level affect pedestrians' and bicyclists' route choices.

5.1 Pedestrians

Our survey found that among the around 55% of pedestrians who stated that they sometimes or very often change route in winter, surface conditions were considered the most important reason for their choice. They stated the desire to avoid slippery surfaces in particular as their main motivation. Snow-covered surfaces that make walking laborious are also an important reason driving the decision to change route.

The association between surface conditions and pedestrian route choice was also supported by the choices the experiment revealed. The winter maintenance LOS does seem to matter when pedestrians choose where to walk; however, it should be noted that the effect sizes are quite small, despite their statistical significance. Even a small amount of snow and slush on the pavement caused a significant number of pedestrians to change their route. During the entire observation period, Side GsB was not exposed to any significant changes in surface conditions. The loose snow layer on the pavement was measured to be approximately 5 cm thick. This amount of snow should have a minimal practical effect; it merely causes a visible difference between the sides. The most surprising finding is that, given the significant change in route choice precipitated by the other surface conditions, partly ice-covered pavement was not associated with a significant change in route, even though this surface condition is arguably the most dangerous on which to walk and is also the reason pedestrians reported the most frequently in the survey, in general, to explain why they choose an alternative route.

One possible reason the ice condition did not lead to a route change is that when Side GsB was partly covered with ice, the visual difference between the two sides was minimal or non-existent compared to when Side GsB was covered with snow or slush. Thus, many pedestrians were likely deceived by the lack of visual difference and chose to walk on a surface that they did not prefer, even when a safe, more attractive option was available. This highlights the importance of correspondence between actual surface conditions and road users' visual perceptions.

Higher age was found to be a good predictor of choosing Side GsB in the experiment. This finding is counterintuitive; that is, it is the opposite effect of what was expected. We would expect older people to be more sensitive to surface conditions and have a higher tendency to choose GsA. It could be that the 60+ group is the most sensitive to surface conditions but is also the group that has the lowest capacity to alter their route choice when they are outside because this will require more effort than it would for younger people. Hence, if one route has a substantially shorter travel time, it might be chosen regardless of the surface conditions. Based on the survey results, the > 60 segment stated they were somewhat more likely than the rest of the sample to choose alternative routes in winter compared to in summer. However, it is difficult to ascertain whether these route choice changes are pre-planned – that is, made before the trip – or if they are adaptations to the road environment the pedestrians encounter while walking outdoors during winter.

5.2 Bicyclists

Like pedestrians, bicyclists often choose alternative routes in winter compared to in summer. In the sample, 32.3% of the bicyclists stated that they sometimes choose alternative routes in winter, while 16.3 % do so often. Approximately one third stated that they do not choose different routes in winter than in summer.

In contrast to pedestrians, bicyclists are more concerned with loose snow and are less likely than pedestrians to change routes because of slippery surfaces. However, there is a gendered divide in the answers: In general, women are more concerned with slippery surfaces than men, which makes females more likely to choose an alternative route. The most probable reason icy pavement surfaces are not more of a deterrent for bicyclists is that almost all the bicyclists in the sample use studded tires when cycling during winter. Since loose snow is laborious to cycle through, many bicyclists avoid it when possible.

As the experimental results demonstrate, surface conditions did not affect which side bicyclists preferred. We have discussed the small variation in the surface conditions on Side GsB during the experimental observation period, which is probably one explanation for why it did not affect bicyclists' route choice. It is likely that if the snow accumulations were higher, this would have manifested itself in bicyclists' route choice as well. In one sense, we can say that we did not observe any critical threshold when surface conditions affected bicyclists' route choice. Other concerns such as travel time, avoiding waiting at the crosswalks, and similar concerns most likely weighed more heavily than discomfort – if any – due to the presence of snow and ice on the pavement during this experiment.

Bicyclists are perhaps more affected by their trip origins and destinations than pedestrians. Owing to the speed difference between pedestrians and bicyclists, if the travel distance is the same, the waiting time to cross the roadway accounts for a higher percentage of overall travel time for a bicyclist than for a pedestrian. This increase in travel time suggests that the time penalty for crossing the road is felt more strongly among bicyclists than pedestrians. Hence, bicyclists prefer simple routes and want to travel in straight directions (Zimmermann et al., 2017). Stinson and Bhat (2003) found that bicyclists tend to avoid traffic lights when choosing their travel routes. Considering these factors, it is plausible that if a bicyclist starts on the GsB side, the threshold to change to Side GsA would be high.

Another potential reason surface conditions did not seem to affect route choice is that bicyclists might have more conflicting considerations than pedestrians regarding what constitutes a good pavement surface. For instance, some bicyclists might avoid salted cycleways because salt leads to bike corrosion, which would incline these people toward GsB. Other bicyclists might feel safer when the asphalt is visible, which would incline them toward GsA. Unfortunately, the survey did not include a category for bicyclists who choose different travel routes in winter compared to in summer due to salt on the pavement. However, other parts of the survey suggest that the cycling community is divided in their opinion on salt usage (Johansson and Bjørnskau, 2020b). This issue needs further investigation and should be a topic for future research.

5.3 General remarks

As the survey results demonstrate, many pedestrians and bicyclists alter their route choices in winter compared to their preferred route in summer. The association between surface conditions and route choice is substantial. In general, bicyclists state that they want to avoid pavement with a build-up of loose snow because it is laborious to cycle through it, while pedestrians want to avoid surfaces that are slippery due to the presence of ice and snow. The experiment revealed that a small amount of snow and slush on a surface is associated with decreased pedestrian use if an alternative bare surface route is available. The same association between winter maintenance LOS and bicyclists' route choices was not found. Plausible reasons for this have been discussed.

It should be noted that the results presented in Table 5 are somewhat different from those Johansson and Bjørnskau (2020a; 2020b) reported. This difference is most prevalent for bicyclists changing routes after encountering ice-covered surfaces. The aforementioned authors reported that 36% of bicyclists change routes very often on ice-covered surfaces, while we report that 20% do this very often. Furthermore, those authors used the entire dataset in their report, while we selected only those cyclists who were very familiar with cycling in winter conditions and lived in areas where the climatic conditions favor snow and ice. This difference indicates that ice is less problematic for experienced winter cyclists than for cyclists who are less experienced with winter cycling.

5.4 Further research

How long of a detour is the average pedestrian or bicyclist willing to walk or cycle to access surfaces that are perceived as more attractive? Unfortunately, the present study cannot answer this question. However, some alternative methods can be used. One could track pedestrians using a global positioning system (GPS), similar to Hulleberg et al.'s (2018) study of bicycle trips in Oslo. One challenge with this approach is that winter surface conditions cannot be assumed to be stable; they can change drastically from day to day and from hour to hour. Therefore, continuous monitoring of road conditions is necessary if this method is used. How long a detour a person is willing to make is most likely correlated with the relative difference between road conditions on the route currently in use versus on the alternative route(s). Monitoring the road conditions in an analysis network can be both costly and challenging to manage in practice. Another approach is to find answers through stated preference surveys. However, as this study shows regarding willingness to change route on icy road surfaces, there might be a mismatch between stated and actual behavior. A third and perhaps the most promising approach is to use drone technology to study actual route choices. Multiple alternative routes can be studied simultaneously by obtaining a bird's-eye perspective of the area of interest. This will enable the researcher to visually ascertain which part of the road is being used, a task that is challenging to manage through GPS data. Surface conditions can also be determined visually, to some extent.

5.5 Implications

From a winter operation and maintenance perspective, we can ask, what is the most important measure to implement in order to make walking and cycling during winter more attractive? Eliminating winter conditions is, of course, impossible in practice. If only one measure was to be implemented, the results of the surveys suggest that the main focus directed toward pedestrians should be to mitigate slipperiness. On the other hand, for experienced winter cyclists, snow clearance resulting in even surfaces is an essential measure.

The experimental results suggest that a small but significant number of pedestrians alter their route choices owing to wintertime surface conditions, even when the amount of snow or slush is minimal. The results also highlight the importance of correspondence between actual surface conditions and pedestrians' visual perceptions. When examining bicyclists, the results were ambiguous. It is unclear whether a bare pavement LOS is more favorable than a winter pavement LOS, given that the surface is kept compact and even.

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Disclosure statement

The authors declare no conflict of interest.

Data availability statement

Some or all data, models, and/or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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B Paper II

Winter walking – The effect of winter conditions on pedestrians' step length and step frequency

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This paper is submitted and awaiting publication and is therefore not included.

C Paper III

The walking speed of pedestrians on various pavement surface conditions during winter

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Abstract

This study aims to quantify the relationship between pedestrians' walking speeds and various surface conditions typically associated with a winter environment. The purpose is to enable assessments of the effects of different winter operation and maintenance regimes on pedestrians' average travel times.

The results show that there is a significant relationship between surface conditions and average walking speeds. When comparing a bare-pavement level of service (LOS) with the practically best obtainable winter-pavement LOS it is expected that the average travel times of an average pedestrian will be approximately 1 min/km longer on the latter than the former when walking on flat ground. On clean ice, compared to a bare pavement, we can expect the average travel times to be approximately 2 min/km longer.

Data on average travel times should be implemented in cost-benefit analyses that evaluate the effects of different winter operation and maintenance regimes and measures.

Keywords

Pedestrians; Walking Speed; Average Travel Time; Winter Operations and Maintenance; Cost-benefit Analyses

1.0 Introduction

In cold regions, weather conditions can vary substantially between seasons. In wintertime, snowfall and freezing and thawing processes affect the pavement surface conditions and can turn the streets and roads impassable. To supply infrastructure that supports an acceptable level of accessibility for all road users, the challenge induced by varying conditions must be overcome.

Some level of winter operation and maintenance is usually required to cope with the problem described above. Snow removal by plowing or scraping, friction increasing measures like sanding or gritting, and some anti- and de-icing applications are typical examples of winter operations conducted on a day to day basis to support efficient and safe travel.

In Norway, where this study is conducted, walking constitutes approximately 1/5 of all daily trips (Hjorthol et al., 2014). Making more people walk more all year round is regarded important to develop healthy and sustainable cities and societies. However, quantified relationships between different winter operations and maintenance regimes, and walking behavior are lacking (Veisten et al., 2019). This is unfortunate because it prevents reasonable assessments of the effects on pedestrian traffic. This paper focuses on the effect of pavement surface conditions on pedestrians' average walking speed and travel times during winter.

1.1 Previous research on walking speed in winter environments

In a review study that describes the most critical factors influencing walking speed and estimates their impact based on existing literature, Bosina and Weidmann (2017) found a significant relationship between air temperature and walking speed. People tend to walk faster in cold temperatures. As the authors describe, this behavior probably occurs because when it is cold, people want to avoid spending too much time outside and faster walking helps keeping the body temperature stable. The relationship between air temperature and walking speed is also supported by finding typical colder months to be associated with higher walking speeds than typical warmer months. In the same study, surface quality is listed as an independent variable that influences the walking speed, but neither its significance nor effect size is estimated.

That colder air temperatures are associated with faster walking speeds is also supported by Liang et al. (2020). By video recordings of a square in the Chinese city Harbin, the authors extracted pedestrian trajectories to calculate behavioral data. During the time of recording, the air temperature varied between +4.0 and -21.8 °C. Their main conclusions are that both the apparent temperature and pavement surface conditions are negatively correlated with average walking speed, which means that the lower the apparent temperature, the faster people walk. Further, when the ground is covered by snow, they report a reduction in average walking speed by about 0.102 m/s compared to a clean ground (Liang et al., 2020). The authors did not report the amount of snow on the ground, whether it was compacted or loose, or whether ice was present on the surface or not.

The same relationship between air temperature and walking speed was found in Knoblauch et al.'s (1996) study of pedestrians' walking speed at crosswalks in signal-controlled intersections. For all pedestrians, meaning both compliers and non-compliers, both younger and older pedestrians walked about 0.1 m/s faster when the temperature was between -12.8 to 6.0 °C than when the temperature was above 14.5 °C. They also measured the effect of weather conditions and walking speed and found that "snow" increases the average walking speed for both groups compared to dry weather conditions by about 0.11 m/s. However, the weather condition categorized as "snow" was quite broad. They defined "snow" as when there was snow or ice in the atmosphere, on the road or sidewalk, or both. Therefore, it is hard to determine whether the precipitation or surface condition caused the measured effect. Even though the average walking speeds tended to increase during "snow" compared to "dry", one of the lowest 15^{th}-percentile walking speeds they measured was for older pedestrians crossing snow-covered roadways.

Montufar et al. (2007) studied seasonality's effect on pedestrians' walking speeds. They investigated the differences between "normal" walking speed and the walking speed to cross a signalized intersection. The study was conducted in Winnipeg, Canada. They found that the average normal walking speed for both older and younger pedestrians was about 0.1 m/s faster in summer than winter, regardless of gender. However, the average crossing walking speed was faster for younger pedestrians in winter than summer, with about 0.06 m/s. For older pedestrians, the average crossing walking speed did not change by season. They investigated two seasons, represented by whether there was snow or ice on the ground or not. The winter months were December, January, and February, and the summer months May and June. They did not report the air temperatures when the data was collected. In a follow-up study, Arango and Montufar (2008) investigated the walking speed of older pedestrians who use walkers or canes for mobility. For this group, they found no difference in average normal walking speed between seasons. However, the average crossing walking speed was significantly higher in winter than in summer, by 0.14 m/s.

In an experimental study, Larsson et al. (2019) explored pedestrian perceptions of fall risk, balance, and footfall transitions while the pedestrians were using different designs for anti-slip devices on ice and snow-covered ice and related these to measurements of walking speed and friction. Nine participants walked on different surfaces using 19 different anti-slip devices and was asked to walk comfortably and rapidly. For most devices, the authors found a speed reduction by the participants when walking at a comfortable speed on ice compared to the clean surface. The maximum walking speed was significantly reduced for all devices when walking on ice and snow-covered ice compared to the clean surface.

In summary, the relationship between air temperature and walking speed seems to be well established. A lower air temperature or apparent temperature is associated with higher walking speeds by pedestrians. The findings of the effect of surface conditions on walking speed, on the other hand, are more uncertain. Larsson et al. (2019) have comprehensive descriptions of the surface conditions and generally find that ice-covered surfaces reduce the walking speed. Liang et al. (2020) also found slower walking speeds when the ground is covered with snow than when it was clear. Some reported studies lacked a clear description of the surface conditions when the observations were made or fail to report the temperature. This makes it difficult to isolate the effects and relate the results to winter operations and maintenance. Few of the stated studies report the amount of snow on the ground and whether it was loose snow or compact snow. Some of the studies make no clear distinction between snow and ice on the ground or if it is snowing or actually a snow-covered surface. The impression, however, is that snow- or ice-covered surfaces are associated with slower walking speed. Perhaps except for the walking speed when crossing a road at an intersection. Why this is the case is not clear. Montufar et al. (2007) raise the hypothesis that it might be because the pedestrians have a lower sense of security when walking on snow while crossing the road. Therefore, they want to minimize their exposure on the road and are unwilling to take any chances. Even though surface conditions seem to impact walking speed, the actual effect of various pavement surface conditions during winter on pedestrians' walking speed is a knowledge gap that needs to be filled.

1.2 Cost-benefit analyses

In a recently published report on socio-economical analyses of operation and maintenance, the "relationship between (operation and maintenance-related) road conditions and mobility, comfortable speed and travel time for cycling/walking" is identified as a knowledge gap that must be filled in order to be able to assess operation and maintenance measures economically (Veisten et al., 2019). In general, several such quantified relationships between maintenance regimes and consequences for pedestrians are lacking. Walking speed, and hence average travel time, is just one aspect that must be assessed for enabling such analyses. In addition, the effects on the risk of injury, the pedestrians' perception of attractiveness and comfort and thus travel choices, operational costs, and environmental concern are other essential aspects.

In a study investigating values of time for different modes of transport in a Norwegian context, walking to or from work on a sidewalk or a walkway has been valued to be approximately €16/hour (2018 values) (Flügel et al., 2020). This value constitutes approximately €0.27/min (2018 values). For other estimates of values of time found in other countries, see Litman (2009).

1.3 Scope of the research

Because of the relationships described in Section 1.1, a study that aims at investigating how different surface conditions typically associated with winter affects walking speeds and other walking characteristics should not compare measurements conducted in relatively colder winter months with measurements conducted in relatively warmer summer months. It seems more reasonable to only compare measurements conducted in winter, but for various surface qualities and control for the effect of air temperature.

The purpose of this paper is to fill the described knowledge gap. Our research question is as follows:

- What is the association between pavement surface conditions typical in a winter environment and pedestrians' walking speed?

Our hypotheses are:

i. There is a negative relationship between air temperature and walking speed.

ii. Pavement surface conditions significantly affect walking speeds.

iii. The impact of pavement surface conditions on walking speed is greater when walking downwards than when walking upwards or on flat ground.

We expect pedestrians to walk slower on snow- and ice-covered surfaces than on asphalt because of fear of slipping and falling and because it is more laborious to walk on. We, therefore, expect the fastest walking speeds to be measured on asphalt, followed by compact snow. Further, that it is faster to walk on a gritted ice pavement than on clean ice. Finally, we expect that it is faster to walk on non-slippery compact snow than on loose snow.

When walking downwards, gravity is working in the same direction as the walking direction. This might further affect the pedestrians' perception of control and decrease their sense of security when walking on slippery surfaces. For this reason, it is plausible that pedestrians will slow down more when walking downwards than if they were walking upwards, where gravity works in the opposite direction of the walking direction or when walking on flat ground.

In contrast to previous research, this study focuses on the actual surface conditions when the measurements are conducted. The purpose is to enable assessments of winter operation and maintenance Level of Service (LOS) and pedestrians' average travel times. In addition to the socio-economic assessments, a better understanding of pedestrians' walking speeds at various surface conditions can also enable more robust modeling of pedestrian traffic in general and specifically during winter.

1.4 Outline of the paper

In Section 2.0, we will describe the method used to answer the research question. In Section 3, the results of the study will be presented. Finally, in Section 4, we will discuss the implications of the results in a broader context and do an example calculation of the socio-economic effect of differences in travel times due to different pavement surface conditions.

2.0 Methods

In order to answer the research question, pedestrians were timed manually by stopwatch by an observer as they walked a distance with a known length. The stopwatch was started as the pedestrians' center of gravity was above the starting point, stopped when it was above the ending point, and the observer registered the time they spent. One observer did all the registrations. Therefore, systematic errors due to different interpretations between observers should be non-existing. The average measuring distance was 18,2 m.

The calculation of the walking speed of a single pedestrian was done using the simple principle of motion:

$$V = \frac{D}{t}$$

where, V = walking speed [m/sec], D = measuring distance [m], and t = time spent walking the distance [sec].

Since the intent was to capture naturalistic behavior, we tried to prevent the pedestrians from being aware that they were being timed. To prevent this, the observer was standing as far as practically possible away from the walkway or sidewalk where the pedestrians were timed, but as close as necessary to precisely detect when the pedestrians passed the start- and endpoint. The observer used regular clothes and hid the stopwatch from sight. The observer tried to avoid spending several days in a row in the same neighborhood to not make the observer recognizable. By chance, two colleagues were timed as they walked in one of the neighborhoods; neither of them had registered the observer when asked afterward.

2.1 Data and analyses

The pedestrians' gender and approximate age were determined by observation. We chose to divide the pedestrians into approximately 16-30, 31-60, and >60 years old age groups. Since the age we have given any pedestrian in the dataset is based on observation, it is impossible to have a very detailed division without making many mistakes in the categorization. However, a division in three with "young (except for children)," "middle-aged," and "older" was deemed practically possible to determine by observation. This is the reason why these three age categories were chosen.

Additional information such as temperature, weather conditions, snow depth, a qualitative description of the friction and surface quality, and whether the pedestrians used any anti-slip device, canes, walkers, or trundling strollers was also collected. In summary, these are the variables used in the calculations:

Dependent variable:

- Walking speed [m/s].

Main independent variable of interest:

- Pavement surface conditions. Divided into the following categories:
    - Asphalt.
    - Compact snow.
    - Loose snow.
    - Gritted ice.
    - Clean ice.

Independent variables (control variables):

- Temperature.
- Age.
- Gender.
- The use of aids like crampons, walkers, strollers.
- Precipitation
- The inclination of the walkway or sidewalk.

The impact of the various control variables on walking speed is expected to be in accordance with Bosina and Weidmann (2017). Based on their findings, we believe that temperature affects walking speed negatively, higher age is associated with slower walking speeds, men walk faster than women, precipitation (snow and rain in the air) increase walking speeds compared to dry conditions, and pedestrians walk slower upwards than downwards and on flat ground. We also believe the use of crampons on icy surfaces increases walking speeds compared to if no such aid is used.

The dataset consists of 2 498 observations of pedestrians walking on different surface conditions. The data have been analyzed using OLS regressions. All analyzes have been done by using the Stata 16 software.

Since we are interested in the effects of surface conditions on walking speed and want to isolate this effect as much as possible and reduce the number of variables, we did not measure the walking speeds of the following pedestrians:

- Pedestrians walking in pair or groups.
- Pedestrians walking with pets.
- People carrying heavy luggage.
- Children.
- Those who for some reason stopped between start and end to view their surroundings or similar.
- Those who were interrupted by other pedestrians and those who were walking in crowds limiting free flow.
- Those whose age or gender could not be determined by observation.
- People running parts of or the whole distance.

The exclusion of some of these pedestrians might seem arbitrary. However, we know that walking in groups or pairs and carrying luggage affect walking speed negatively (Bosina and Weidmann, 2017). Groups and pairs of pedestrians, on average, walk slower than single pedestrians, and pedestrians carrying luggage walk slower than those who do not carry luggage. There is no reason to believe that surface conditions will affect a group of pedestrians significantly different than a single pedestrian, only that the average speed of the former on average will be slower. Children are not included in the data because we registered very few children walking in the neighborhoods when we did our observations.

To make sure that the timed pedestrians had free flow and were not interrupted by other pedestrians, we only timed those pedestrians who walked from the start- to the endpoint without passing any other road user moving in the same direction as those we measured or who walked close behind any other road user. If the timed pedestrians walked past any road user moving in the opposite direction, we did not include them in the dataset if they had to make any maneuvers (moving to the sides or similar) to avoid them.

2.2 Study sites and data collection

The observations and measurements were conducted in Trondheim, Norway, a city with about 200 000 inhabitants. The data was collected between November 2019 and March 2020, from the first day of snowfall this season until the winter period ended. The average temperature in this period was approximately 0.8 °C, ranging between -12 °C and 8 °C.

Four neighborhoods were chosen as sites for the observations. They were chosen based on both their similarities and differences. They were similar in the sense that the pedestrian volumes usually are high, the infrastructure is similar, they have low volumes of car traffic, they have similar surroundings, and the winter maintenance LOS on different parts of the street network varied in each neighborhood. They are, however, different in the sense that the demographics of the pedestrians usually walking at the different sites vary between them. Many older people inhabit one of the neighborhoods. One neighborhood was chosen next to the university campus, where many younger people usually walk. Two neighborhoods were chosen with relatively high numbers of commuting trips by foot. Observations and measurements were conducted on a few different walkways and sidewalks in each neighborhood. The measurements were not conducted close to any intersections, but rather on more extended straight walkways or sidewalks separated from car traffic. All measurements were conducted on flat surfaces, except for a particular walkway next to the university campus where we wanted to test how the interaction between inclination and surface condition affect the walking speed. The inclination of this walkway is 8 %.

The observations were conducted on weekdays in the timespans 07.30-09.00 and 15.00-17.00 for three of the sites, namely the university area and the two commuting areas. For the fourth area with higher volumes of older pedestrians, the observations were conducted between 11.00-16.00. The reason for this was that we, for the most part, wanted to measure trips to or from work or the university because we believe that the value of time is highest at these times and that people wish to travel from their origin to their destination as fast as possible for these trips. In contrast to this expectation, daytime or whether the measurements are conducted in rush-hour or not does not seem to influence walking speeds (Bosina and Weidmann, 2017). However, to be sure, we wanted to reduce the effect trip purpose, and daytime could produce and did most of the measurements during rush-hours. For the fourth site populated by many older people, the observation time was chosen based on when the area's residents usually were outside walking. By observing the pedestrian volumes in a pilot study in the previous fall, we learned that few older pedestrians in this neighborhood were outside walking during the rush hours. Data were collected in each neighborhood when there was snow on the ground, ice on the ground, and a clean asphalt surface.

2.3 Descriptions of the analyzed surface conditions

None of the surface conditions were manipulated for this study. The surface conditions were whatever happened to be present at the time the observations were conducted. Since the neighborhoods we chose as study sites "naturally" had different winter maintenance LOS on the various walkways and sidewalks, each surface condition at some point was present in each neighborhood. The classification of the different surface conditions and how they were determined are described in the following sections.

2.3.1 Asphalt

To be classified as “Asphalt”, the whole surface where the measurements were conducted had to be black, without any snow, ice, or gravel present on the surface. The winter operation method used to obtain this level of service is usually referred to as “sweep-salting” in the literature (Niska and Blomqvist, 2019). The walkways and sidewalks are swept by a vehicle with a rotating brush (a front-mounted power broom) for snow clearance. The same vehicle is also equipped with a salt spreader. Salt is applied before and during snowfall to prevent compaction and on wet pavements when there is a danger of freezing.

Figure 1 Surface conditions categorized as "Asphalt"

2.3.2 Compact snow

To be classified as “Compact snow”, the whole surface where the measurements were conducted had to be compacted snow. Another requirement was that the compacted snow was not slippery and that the surface was approximately even. If the snow was polished enough to reduce the friction and making the surface slippery, and no friction increasing methods had been used, the surface condition was instead classified as “Gritted ice”. In practice, this means that “Compact snow” is the best possible surface condition for a walkway maintained as a winter-pavement LOS. The winter operation method used to obtain this service level involves plowing for snow clearance and scraping or gritting to increase the friction if needed. Salt is typically not applied in this method.

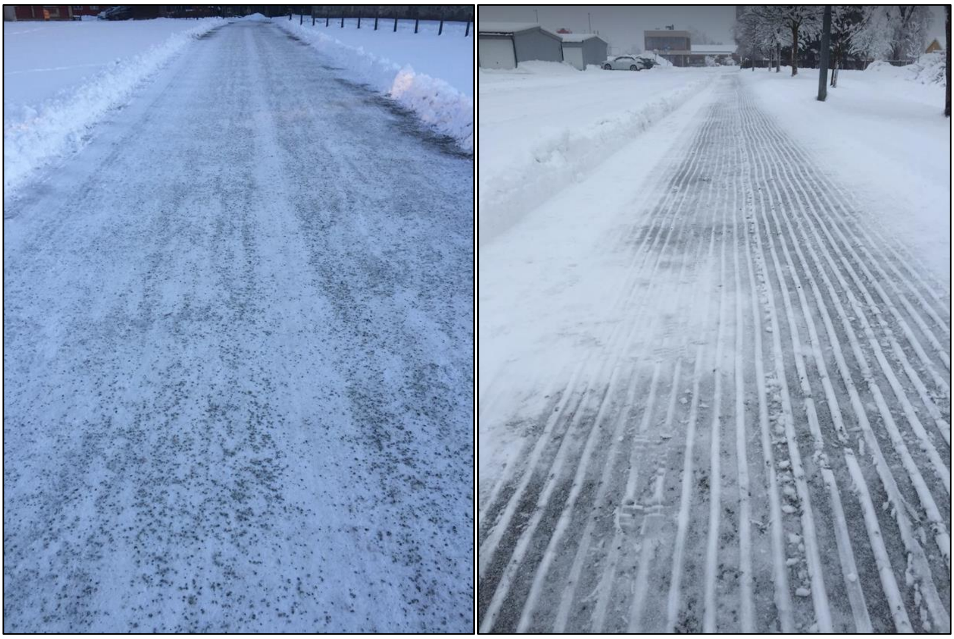

Figure 2 Surface conditions categorized as "Compact snow"

2.3.3 Loose snow

To be classified as “Loose snow 2-8cm”, the whole surface where the measurements were conducted had to be loose snow with a snow depth between 2 to 8 cm. Another requirement was that ice was not present beneath the snow. This means that beneath the snow, either asphalt or a compact snow layer could be present. When either the snow was cleared by maintenance vehicles or the pedestrians had compacted it by walking over it repeatedly, the measurements were stopped. A loose snow layer is usually present on a walkway between a maintenance vehicle’s cycles or on a walkway that is not maintained. In some cases, loose snow on the pavement can result from requirements in operation contracts to start plowing when the snow depth is a certain amount and not before. The reason that 8 cm is the upper limit for snow-depth is that no measurements were conducted on any surface with a bigger snow depth.

Figure 3 Surface conditions categorized as "Loose snow 2-8cm"

2.3.4 Gritted ice

To be classified as “Gritted ice”, the whole surface where the measurements were conducted had to be either an ice surface that was gritted or a polished compact snow layer that was gritted or had a rough surface. In practice, this is the state of a walkway maintained as a winter pavement when traffic has polished the snow, making it slippery, or a surface where ice has formed, and gravel is used as a friction increasing method. Freezing and thawing processes on a compact snow surface can also make it slippery, as shown in the picture to the right in Figure 4. In other words, this category can be regarded as the intermediate state between what we have classified as compacted snow and ice.

Figure 4 Surface conditions categorized as "Gritted ice"

2.3.5 Ice

To be classified as “Ice”, the whole surface where the measurements were conducted had to be covered by visible ice. If any friction-increasing methods like gravel were used or salt was used as a de-icer, the pavement surface was not classified as “Ice”. We did neither allow any loose or compacted snow to be present above the ice. In practice, this is perhaps the worst-case scenario (if we disregard a walkway with a buildup of a large amount of snow) when little or insufficient maintenance efforts are made.

Figure 5 Surface conditions categorized as "Ice"

3.0 Results

In the analyses, we have divided the observations into three parts based on whether the walkway or sidewalk had any slope or not. Most of the observations are on flat ground, and the rest are on a walkway with a slope of 8 %. For the walkway with slope, we have divided the observation in two, based on whether the pedestrians walked upwards or downwards. Model 1 is the model for flat ground (n = 1631), Model 2 is the model for a slope of -8 % (n = 472), and Model 3 is the model for a slope of +8 % (n = 395).

3.1 Descriptive statistics

The frequency distributions of the different variables are presented in Table 1. Table 1 shows one column for each model, and each model is split into the different age groups.

Table 1 Frequency table. The table displays each variable's number of observations for the three different age groups in the three models

	Model 1 Flat ground			Model 2 Slope = -8 %			Model 3 Slope = 8 %		
Age groups	Young	Middle-aged	Older	Young	Middle-aged	Older	Young	Middle-aged	Older
Asphalt	164	208	87	95	17	1	71	18	1
Compact snow	159	126	152	66	20	1	116	43	2
Loose snow	108	69	98	2	4	0	25	8	0
Gritted ice	55	45	57	152	61	1	70	34	1
Ice	180	81	42	45	7	0	6	0	0
Females	332	281	257	164	51	0	145	46	1
Males	334	248	179	196	58	3	143	57	3
Did not use crampons	666	513	418	358	103	3	288	101	4
Did use crampons	0	16	18	2	6	0	0	2	0
Did not roll a stroller	664	505	435	360	109	3	288	103	4
Did roll a stroller	2	24	1	0	0	0	0	0	0

Did not use a walker	666	529	395	360	109	3	288	103	4
Did use a walker	0	0	41	0	0	0	0	0	0
Total	666	529	436	360	109	3	288	103	4

As seen in Table 1, some variables have very few observations, for example, the number of older pedestrians in Model 2 and Model 3. This must be taken into consideration when interpreting some of the results. Table 1 should not be used to find the probability of, for instance, how more likely or unlikely older people are of walking outside when there is ice present on the pavement surface. This is because the time and the number of days spent at each site for doing the measurements are not consistent, and the demographics at each site varied.

The empirical cumulative distribution functions of walking speeds on each of the analyzed pavement surface conditions are presented in Figure 6. From Figure 6, it seems like there is an association between walking speed and surface conditions. It seems like the walking speeds on asphalt, in general, are faster than those on snow or ice-covered surfaces. More descriptive statistics from the analyses are presented in Appendix A.

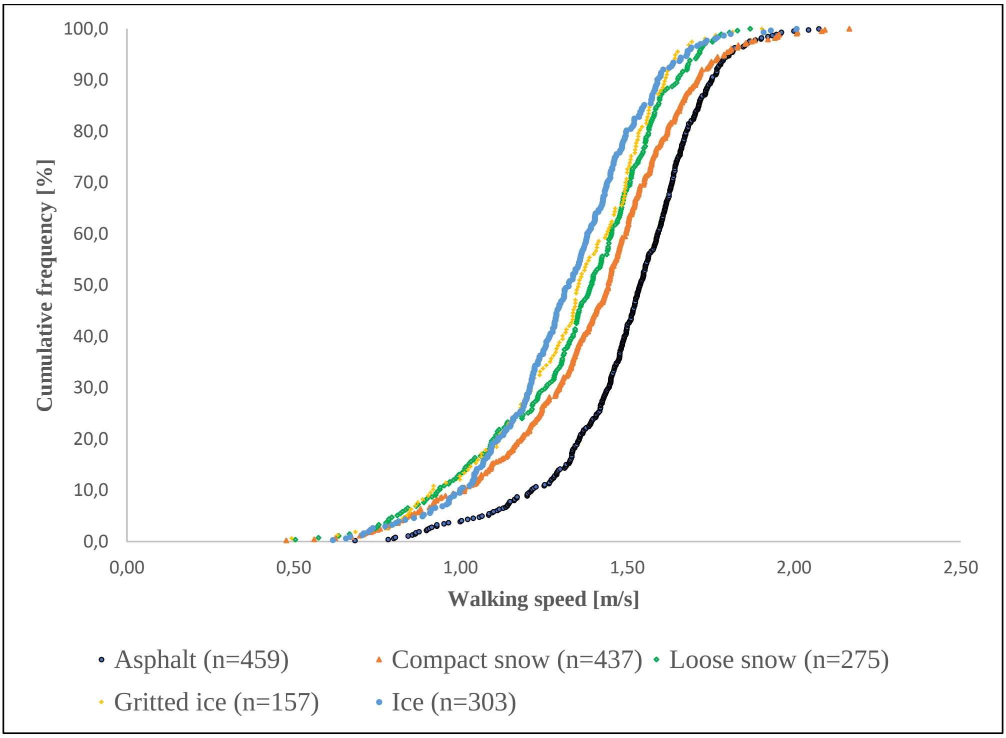

Figure 6 Empirical CDFs for walking speed on the different pavement surface conditions on flat ground

3.2 OLS models

In Table 2, the results of our final analyses are presented. Using OLS regression, we have predicted the walking speed in meters/second based on our independent variables. As can be seen, only the main effects are estimated in the models. We also did estimations of walking speed with interaction terms between surface condition, age, gender, and the use of aids. However, these interactions were not statistically significant and therefore excluded from our final models. We did also include precipitation in our first models. Precipitation did not significantly affect walking speeds and was also excluded from our final models. We have also investigated whether the neighborhood the data was collected in affected the results. As can be seen from Table A.2 in Appendix A, it did not. Therefore, a potential difference in trip purpose because of the neighborhoods' characteristics does not seem to affect the results.

Table 2 Linear regression models predicting walking speed [m/s]. Model 1 is the model for walking on flat ground. Model 2 is the model for walking downwards, slope = -8 %. Model 3 is the model for walking upwards, slope = 8 %

	Model 1 Walking speed [m/s] (Flat ground)	Model 2 Walking speed [m/s] (Slope = -8 %)	Model 3 Walking speed [m/s] (Slope = 8 %)
Constant	1.600***	1.611***	1.470***
	(0.01)	(0.02)	(0.02)
Temperature	-0.013***	0.000	-0.002
	(0.00)	(0.00)	(0.00)
Asphalt	0	0	0
	(base)	(base)	(base)
Compact snow	-0.108***	-0.038	-0.064***
	(0.01)	(0.03)	(0.02)
Loose snow (2-8cm)	-0.133***	-0.102	-0.110***
	(0.01)	(0.08)	(0.03)
Gritted ice	-0.151***	-0.127***	-0.097***
	(0.02)	(0.02)	(0.02)

Ice	-0.255***	-0.178***	-0.043
	(0.01)	(0.03)	(0.06)
Female	0	0	0
	(base)	(base)	(base)
Male	0.081***	0.118***	0.132***
	(0.01)	(0.02)	(0.01)
Young	0	0	0
	(base)	(base)	(base)
Middle-aged	-0.072***	-0.037	-0.087***
	(0.01)	(0.02)	(0.02)
Older	-0.351***	-0.449***	-0.290**
	(0.01)	(0.10)	(0.07)
Did not use crampons	0	0	0
	(base)	(base)	(base)
Did use crampons	0.075*	0.104	0.064
	(0.03)	(0.07)	(0.10)
Did not roll a stroller	0	-	-
	(base)		
Did roll a stroller	-0.095**	-	-
	(0.04)		

Did not use a walker	0 (base)	-	-
Did use a walker	-0.333*** (0.03)	-	-
Observations	1631	472	395
R^2	0.539	0.206	0.274

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

3.3 Model 1 (flat ground)

For each degree Celsius increase in temperature, the walking speed is reduced by 0.01 m/s, at least in the interval we have observations of, that is between -12 to 8 °C. Males, on average, walk 0.08 m/s faster than females. There is also a reduction in average walking speed as age increases. Older pedestrians that use a walker, on average walk 0.33 m/s slower than those that do not in this age group. Using crampons as an anti-slip device increase the walking speed by 0.08 m/s, on average.

Walking on compact snow, on average, reduces the walking speed of pedestrians by 0.11 m/s compared to walking on asphalt. When the ground is covered by loose snow with a depth between 2-8 cm or gritted ice, the average walking speed is 0.13 m/s and 0.15 m/s slower than when walking on asphalt. The surface condition with the most prominent effect on walking speed is found when the ground is covered by clean ice. On an ice-covered surface, the average walking speed is 0.26 m/s slower than on an asphalt surface.

Figure 7 shows the predictive margins of surface condition on walking speed based on model 1. The predictive margin for each surface condition represents the average predicted walking speed if everyone in the sample (from Model 1) had walked on that particular surface condition, and all other variables are left unchanged. By observing the confidence intervals, we see that the walking speed on compact snow, loose snow, and gritted ice is significantly different from the walking speed on asphalt. However, we can not be certain that the walking speed on loose snow between 2-8 cm and gritted ice is significantly different from the walking speed on compact snow.

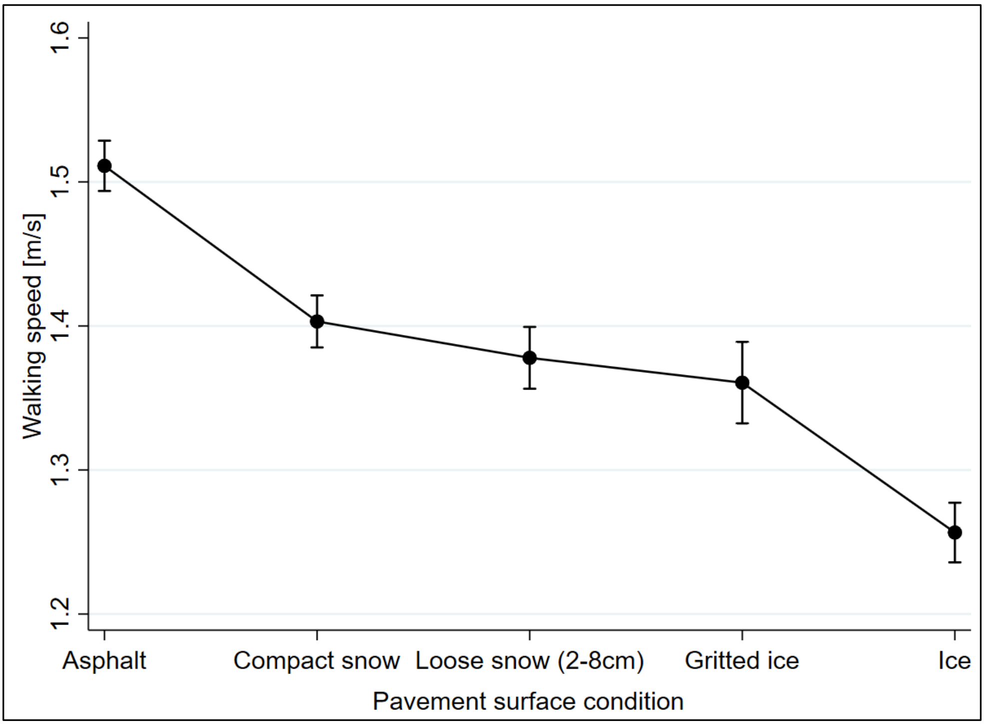

Figure 7 Predictive margins of surface condition with 95 % Confidence intervals, calculated from Model 1

Using the walking speeds calculated in Model 1 and shown in Figure 7, we can calculate the average travel times on different surfaces. In Table 3, the average travel time per km for the different surfaces are calculated.

Roughly, we can assume that walking on a surface covered with snow or gritted ice makes the travel time approximately 1 min longer per km than when walking on asphalt. When walking on ice, a pedestrian, on average, will use more than 2 min longer per km than when walking on asphalt.

3.4 Model 2 (downwards)

When walking downwards, the temperature does not seem to influence the walking speed. Males, on average, walk 0.12 m/s faster than females. As age increases, the average walking speed decreases.

The difference in walking speed on asphalt and compact snow is not statistically significant. Neither is the difference on loose snow, but the number of observations on loose snow is very limited. When the surface turns slippery due to ice, the difference in walking speed compared to walking on asphalt turns significant. The average walking speed on gritted ice is 0.13 m/s slower than on asphalt. On clean ice, the average walking speed is 0.18 m/s slower than on asphalt. The predictive margins of surface conditions on walking speed for walking downwards on a slope of -8 % are presented in Figure 8.

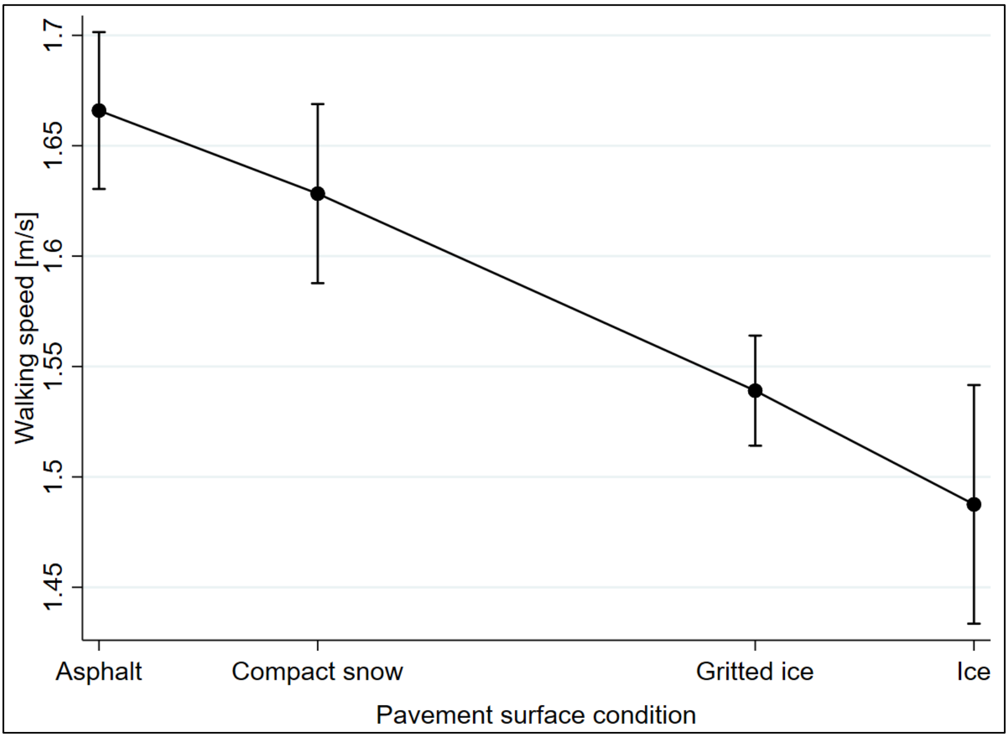

Figure 8 Predictive margins of surface condition with 95 % Confidence intervals, calculated from Model 2

The tendencies are similar to walking on flat ground. The walking speeds, on average, are faster than on flat ground. The confidence intervals are broader than in Figure 8, most likely due to a smaller sample size. The calculated travel times when walking downwards are presented in Table 3. We can expect the average travel time to be approximately 1 min/km slower on gritted ice and clean ice than when walking on asphalt.

3.5 Model 3 (upwards)

When walking upwards, the temperature does not seem to influence the walking speed. Males, on average, walk 0.13 m/s faster than females. As age increases, the average walking speed decreases.

When walking on compact snow, the average walking speed is 0.06 m/s slower than when walking on asphalt. On loose snow and gritted ice, the average walking speeds are 0.11 m/s and 0.10 m/s slower than when walking on asphalt, respectively. The effect of clean ice on walking speed is not significantly different from the speed on asphalt, but this is because there are almost no observations of pedestrians walking on clean ice. The predictive margins of surface conditions on walking speed for walking upwards on a slope of 8 % are presented in Figure 9.

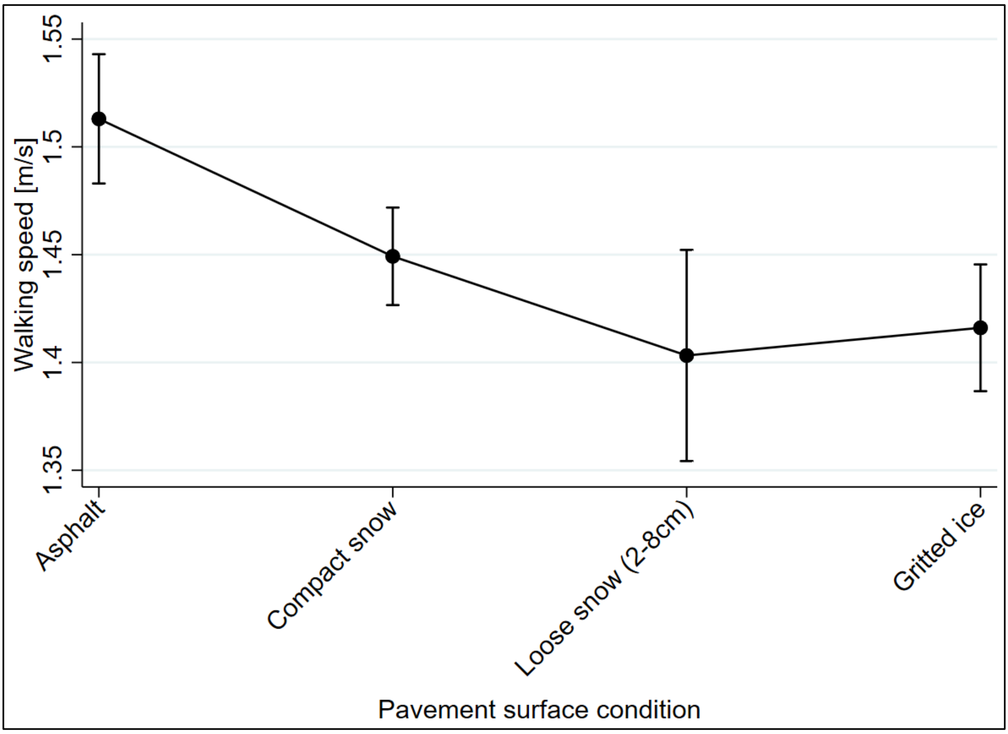

Figure 9 Predictive margins of surface condition with 95 % Confidence intervals, calculated from Model 3

The calculated travel times when walking upwards are presented in Table 3. On compact snow, we can expect the average travel time to be 0.5 min/km slower than when walking on asphalt. We can expect the travel time to be almost 1 min/km slower on loose snow and gritted ice than when walking on asphalt.

3.6 Calculated travel times

The average walking speeds both upwards and downwards, in general, are faster than when walking on flat ground. The reason for this is the difference in demographics in the different samples in the three models. The older age group is not represented in the models for upwards and downwards walking, and the proportion of the younger and middle-aged pedestrians is different from Model 1, as shown in Table 1.

Table 3 Average walking speeds, average travel times, and differences in average travel times on the various surface conditions analyzed

Inclination	Pavement surface condition	Average walking speed [meters/second]	Travel time (T_i) [seconds/km]	Δ Travel time (T_i - $T_{Asphalt}$) [seconds/km]
Flat ground	Asphalt	1.511	662	0 (base)
	Compact snow	1.403	713	+51 (+7.7%)
	Loose snow	1.378	726	+64 (+9.7%)
	Gritted ice	1.361	735	+73 (+11.0%)
	Ice	1.257	796	+134 (+20.2%)
Downwards	Asphalt	1.666	600	0 (base)
	Compact snow	1.628	614	+14 (+2.3%)
	Loose snow	N.D.	N.D.	N.D.
	Gritted ice	1.539	650	+50 (+8.3%)
	Ice	1.488	672	+72 (+12.0%)
Upwards	Asphalt	1.513	661	0 (base)
	Compact snow	1.449	690	+29 (+4.4%)
	Loose snow	1.403	713	+52 (+7.9%)
	Gritted ice	1.416	706	+45 (+6.8%)
	Ice	N.D.	N.D.	N.D.
Flat ground*	Asphalt	1.607	622	0 (base)
	Compact snow	1.499	667	+45 (+7.2%)
	Loose snow	1.476	678	+56 (+9.0%)
	Gritted ice	1.467	682	+60 (+9.7%)
	Ice	1.351	740	+118 (+19.0%)

* The older pedestrians are omitted for better comparison to Model 2 and Model 3 and to isolate work-related trips and trips to and from the University.

For a better comparison between the three models, we have removed the older pedestrians when walking on flat ground and calculated the walking speeds and travel times in the bottom rows of Table 3. The differences in travel times did not change significantly (between 6 seconds on compact snow to 16 seconds on ice). However, as expected, the average walking speeds increased when we removed this age group from the analysis.

4.0 Discussion

The negative relationship that was expected between temperature and walking speed was confirmed in Model 1. When walking on flat ground, we found increasing walking speeds as the temperature was decreasing. However, we found no association between temperature and walking speed when walking upwards or downwards.

The results show that our hypothesis that pavement surface conditions during winter significantly affect walking speeds is confirmed. When pedestrians are confronted with snow- and ice-covered surfaces, they reduce their walking speed compared to walking on asphalt. The range in increased travel times is between approximately 1-2 minutes longer per kilometer than walking on asphalt, dependent on the type of surface they are walking on. The implications of these increased travel times from an economic point of view will be discussed in Section 4.2.

The hypothesis that the impact of surface conditions on walking speed is greater when walking downwards than when walking upwards or on flat ground is rejected based on the results. There was no evidence from the data to support this claim. Contrary, if anything, it seems like the impact of pavement surface conditions on walking speed is greater when walking on flat ground. However, the sub-samples used in Model 2 and Model 3 might not be representative of the overall population, like in Model 1, since they are collected on a single site. Therefore, more data from different sites should be used if this hypothesis should be investigated further.

4.1 The results seen in the context of previous research

Table 4 summarizes the previous research on walking speed in winter environments. Table 4 includes the main results from our study to ease comparisons.

The reduction of walking speed by 0.11 m/s when walking on compact snow compared to walking on asphalt on flat ground is in accordance with Liang et al. (2020)’s findings from China, even though they did not report if the snow was loose or compacted, or if there were any ice present on the ground. They found that when the ground was covered with snow, the average walking speed decreased by about 0.102 m/s compared to when the ground was clean. However, it should be noted that even though the relationship is equal, the average walking speed they found is substantially lower than the one found in the present study. This difference might have several explanations. The most prominent explanation is the type of environment the data is collected. The present study has focused on commuting trips on straight sidewalks or walkways. Liang et al. (2020)’s study site is an open square with more recreational trips, and they have actively avoided measuring commuting trips by doing their measurements during weekends. This can affect the average walking speeds obtained. Another potential reason can be cultural differences. This is rather unlikely, because even though there seems to be some differences in walking speeds between continents, the differences are not significant (Bosina and Weidmann, 2017).

Table 4 A summary of the previous research and this study on the walking speed of pedestrians in winter environments

Study	Topic/goal	Method of measurement	Differentiates between seasons?	Differentiates between surface conditions during winter?	Main statement related to walking speed in winter environments	Reported average walking speeds [m/s]
Bosina and Weidmann (2017)	Review article	-	Yes	No	There is a significant negative relationship between air temperature and walking speed	Average overall = 1.34 Temperatures between -5–5°C = 1.45 Temperatures between 5-15°C = 1.40 Temperatures between 15-25°C = 1.34 Women = 1.29 Men = 1.39
Liang et al. (2020)	Investigate how weather affects pedestrians' walking speed in cold environments	Video-recordings	No	Yes	There is a significant negative relationship between air temperature and walking speed Pedestrians walk slower on snow-covered surfaces than on clean surfaces	Average overall = 1.02 The authors report an unstandardized beta coefficient of apparent temperature equal to -0.004 0.10 m/s slower walking speeds on snow-covered ground than on clean ground
Knoblauch et al. (1996)	Quantify the walking speed of pedestrians of various	Manual recording	Yes	Somewhat	There is a significant negative relationship	Younger pedestrians "dry" = 1.47

	ages under different environmental conditions	using a stopwatch			between air temperature and walking speed In general, faster walking speeds during weather conditions categorized as "snow" than "dry"*	Younger pedestrians "snow" = 1.60 Younger pedestrians "low temp" = 1.60 Younger pedestrians "high temp" = 1.48 Older pedestrians "dry" = 1.23 Older pedestrians "snow" = 1.34 Older pedestrians "low temp" = 1.34 Older pedestrians "high temp" = 1.24
Montufar et al. (2007)	Investigate the walking speeds of pedestrians by seasonal conditions	Manual recording using a stopwatch	Yes	No	Faster walking speeds during summer than during winter	Younger pedestrians "summer" = 1.40 Younger pedestrians "winter" = 1.31 Older pedestrians "summer" = 1.18 Older pedestrians "winter" = 1.08
Arango and Montufar (2008)	Investigate the walking speed of older pedestrians using walkers or canes for mobility in a	Manual recording using a stopwatch	Yes	No	No difference between the walking speeds measured during summer and winter	Older pedestrians "summer" = 0.78 Older pedestrians "winter" = 0.77

	real-life environment					
Larsson et al. (2019)	Explore pedestrians' walking speeds while using different designs for anti-slip devices on ice and snow-covered ice**	Manual recording in an experimental setting	No	Yes	The participants tended to walk a bit slower on the ice track with most anti-slip devices compared to their comfortable walking speed at baseline On snow-covered ice, the speed was significantly reduced for one device	Median comfortable walking speed baseline = 1.39 Median maximum walking speed baseline = 1.92 Average of the reported median comfortable walking speeds for all devices on snow-covered ice = 1.40*** Average of the reported median maximum walking speeds for all devices on snow-covered ice = 1.61*** Average of the reported median comfortable walking speeds for all devices on uncovered ice = 1.33*** Average of the reported median maximum walking speeds for all devices on uncovered ice = 1.56***
This study	Investigate the association between pavement surface conditions and	Manual recording using a stopwatch	No	Yes	Pavement surface conditions during winter significantly affect pedestrians walking speeds	Pavement surface condition: "Asphalt" = 1.51 "Compact snow" = 1.40 "Loose snow" = 1.38 "Gritted ice" = 1.36

	walking speed during winter	"Clean ice" = 1.26

*Defined by the authors as: "Dry: clear (no precipitation), with dry roads and dry sidewalks. Snow: when there was snow or ice in the atmosphere, on the road or sidewalk, or both". Low temperature is the interval -12.8 to 6 °C and high temperature is >14.5 °C (Knoblauch et al., 1996).

**We have re-written their research goal for better comparison with the other studies. Their own description of the research goal is: "This study explores pedestrian perceptions of fall risk, balance, and footfall transitions while using different designs for anti-slip devices on ice and snow-covered ice and relates these to measures of gait speed and friction" (Larsson et al., 2019).

*** These numbers were not reported in the study but calculated by us from their reported median walking speeds for each individual anti-slip device.

The effects of the independent variables like age, gender, and temperature are also in accordance with previous research. Bosina and Weidmann (2017) report that men walk 0.1 m/s faster than women and that walking speed decrease with age. The effect size we measured was a 0.08 m/s difference between men and women on flat ground, and we also found a reduction in average walking speed by increasing age. The effect of air temperature we found has the same negative relationship found in previous research. Liang et al. (2020) measured a 0.004 m/s reduction in walking speed for each °C increase in air temperature. In contrast, we measured a 0.01 m/s reduction in walking speed for each °C increase in air temperature. The difference might stem from the fact Liang et al. (2020) have measured walking speeds at colder temperatures than we did in the present study (4.0 and -21.8 °C), and that they have used apparent temperature rather than the air temperature. Apparent temperature is probably a better indicator when predicting walking speed than the air temperature. It can also be questioned whether there is a linear relationship between walking speed and air temperature for a wide temperature interval. It is possible that the relationship is curve linear, rather than linear. The lowest air temperature Bosina and Weidmann (2017) have found measurements for was approximately -10 °C, so it is difficult to determine this definitively.

4.2 Implications for planning

Most of the effects of the different surface conditions on walking speed from our data are moderate. The average travel distance for daily trips by walking in Norway is approximately 2.2 km, and 80 % of these trips are shorter than 3 km (Hjorthol et al., 2014). In the best-case scenario, if a winter-pavement LOS is chosen where one can keep the snow surface compact and non-slippery, we can expect an increased travel time of approximately 112 seconds for each individual compared to if a bare-pavement LOS was chosen for this travel distance. If an ice-covered pavement is gritted, we can expect a travel time reduction of approximately 134 seconds for this distance, compared to not gritting the ice surface. If we compare the best surface condition (asphalt) with the worst (ice) from our study, the difference in travel time for a 2.2 km long trip is almost 5 minutes.

From an individuals' point of view, these increases in travel time might seem neglectable. However, when adding each individuals' travel times, the chosen LOS socio-economic effect might be substantial. This will depend on the number of affected pedestrians.

4.2.1 Example

For the sake of argument, if we assume that 200 pedestrians that walk 2.2 km to and from work have their route upgraded from a surface covered with compact snow to an asphalt surface, the socio-economic benefit due to the travel time gains the pedestrians get from the upgrade can be calculated as follows:

$$\frac{200\,pedestrians}{day} * 2 * 2.2\,km * \left(\frac{45\,sec}{km} * \frac{1\,min}{60\,sec}\right) * \frac{\frac{€0.27}{min}}{pedestrian} = \frac{€178.2}{day}$$

We have multiplied by two since we have assumed that the 200 pedestrians walked both to and from work, meaning that 400 work-related trips were walked this day on this route. The upgrade might also make some that did not walk this route before the upgrade will do so after the upgrade; this effect is not included in the example calculation, but it is discussed below. We have assumed a value of time of €0.27/min, as described in Section 1.2. The value of 45 sec/km was derived from Table 3 and is the average difference in travel time between a surface covered with compact snow and asphalt for work-related trips.

As seen from this hypothetical example, the improved maintenance resulting in a clean asphalt surface instead of a surface covered with compact snow generate a benefit of €178.2/day because of the travel time gains the pedestrians get. The purpose of the example is to illustrate how travel times can be implemented as a part of a cost-benefit analysis that evaluates winter operations and maintenance. If being a factual cost-benefit analysis, other costs and benefits associated with the measure should also be considered: The most important ones, perhaps being the operational costs of the improved maintenance, effects of induced demand, effects on injury risks, and environmental costs due to salting.

Winter operations and maintenance likely affect travel behavior in many ways not explored in this paper. Rantakokko et al. (2009) found that poor street conditions correlate with a fear of moving outdoors for many older people. Hence, snowy and icy streets can affect their willingness to walk outdoors. The association between pavement surface conditions and willingness to go outdoors was also found by Johansson and Bjørnskau (2020). They report that four out of ten would have gone out more often if snow and ice removal was improved. They also found a relationship between route choice and surface conditions. Some studies find a relationship between injuries and pavement surface conditions in a winter environment (Öberg, 1998; Björnstig et al., 1997). Öberg (1998) found a six to eight higher injury risk on snow- and ice-covered surfaces during winter than during summer. These and similar effects also have great implications for the planning and design of winter operations and maintenance.

4.3 Further research

A topic for further research is to look at more extreme events during winter. Our purpose was to investigate typical surface conditions that are present on a day to day basis during winter. After extreme events like snowstorms, the ground conditions can get severely worse than those we have investigated. How do such events affect walking speed and travel times? Worse surface conditions can also be present on sidewalks and walkways were winter operations are neglected. A typical example is if the snow on a roadway is plowed to the sidewalk or walkway where due to freezing and thawing, the surface gets uneven and slippery if it is not removed. The walking speeds and travel times on such conditions would also be interesting to look at.

Travel time is just one aspect that should be considered when choosing a winter operation and maintenance LOS to promote pedestrian traffic. Other essential factors are the risk of injuries, the pedestrians' perception of attractiveness and comfort, operational costs, and environmental concerns. Most of these quantitative relationships need further investigation, and when these relationships are found, they should be implemented in cost-benefit analyses.

4.4 Limitations of the research

Using a stopwatch for the measurements can be associated with errors. Studies using direct manual timing have been found to, on average, report 5 % higher walking speeds than studies using manual data extraction from video recordings (Bosina and Weidmann, 2017). Therefore, there is a possibility that all reported walking speeds in this study are a little overestimated. However, the relative error between the measured walking speeds on the different surface conditions reported in this study should be minimal since one observer did all the measurements using the same procedure each time.

5.0 Conclusion

The results show that there is a significant relationship between surface conditions and average walking speeds. Snow- and ice-covered surfaces are associated with slower walking speeds by pedestrians than when walking on asphalt during winter.

These results should be used to determine the economic costs and benefits associated with faster or slower travel times when assessing the design and planning of operations and maintenance in a winter environment. The results can also be implemented in transport models to better predict pedestrians walking speeds or to anyone interested in walking behavior in a winter environment.

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Declaration of 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.

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Appendix A – Model variations and descriptive statistics

Table A.1 presents a comparison between the inclusion and exclusion of the control variables in Model 1. As seen, the effect of surface conditions on walking speed is very similar whether the control variables are included or not.

Table A.1 A comparison between the effect of surface conditions on walking speed with the inclusion and exclusion of control variables in Model 1

	Walking speed [m/s] when the control variables are omitted from the analysis	Walking speed [m/s] when control variables are included in the analysis (Model 1)
Constant	1.511***	1.600***
	(0.01)	(0.01)
Asphalt	0	0
	(base)	(base)
Compact snow	-0.113***	-0.108***
	(0.02)	(0.01)
Loose snow (2-8cm)	-0.167***	-0.133***
	(0.02)	(0.01)
Gritted ice	-0.185***	-0.151***
	(0.02)	(0.02)
Ice	-0.199***	-0.255***
	(0.02)	(0.01)
Observations	1631	1631
R^2	0.086	0.539

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

In Table A.2, we have re-run Model 1 when the neighborhood the data was collected in, and precipitation are included as independent variables. In the first column of Table A.2, all observations on flat ground are included, while the second column shows the results when the older pedestrians are omitted from the analysis.

Table A.2 An OLS model to test whether the neighborhood the data was collected in and precipitation affect the results. Only the observations on flat ground are included

	Walking speed [m/s] All observations on flat ground	Walking speed [m/s] When the older age group is omitted from the analysis
Constant	1.603***	1.605***
	(0.02)	(0.02)
Temperature	-0.013***	-0.014***
	(0.00)	(0.00)
Compact snow	-0.109***	-0.109***
	(0.01)	(0.02)
Loose snow (2-8 cm)	-0.129***	-0.131***
	(0.02)	(0.02)
Gritted ice	-0.151***	-0.142***
	(0.02)	(0.02)
Ice	-0.255***	-0.256***
	(0.01)	(0.01)
Males	0.081***	0.078***
	(0.01)	(0.01)
Middle-aged	-0.072***	-0.073***
	(0.01)	(0.01)
Older	-0.352***	

	(0.01)	
Did use crampons	0.073*	0.078
	(0.03)	(0.04)
Did roll a stroller	-0.095**	-0.107**
	(0.04)	(0.03)
Did use a walker	-0.334***	
	(0.03)	
Neighborhood[1]	-0.004	-0.005
	(0.01)	(0.01)
Precipitation	-0.012	-0.004
	(0.01)	(0.02)
Observations	1631	1195
R^2	0.539	0.288

Base categories: Asphalt, Females, Younger pedestrians, Did not use crampons, Did not roll a stroller, Did not use a walker, The neighborhood where most of the older pedestrians were timed.

Standard errors in parentheses

[1] The two commuting neighborhoods and the university area.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

As seen, neither neighborhood characteristics nor precipitation significantly affects the predicted walking speeds.

The descriptive statistics for the continuous variables in Model 1-3 are presented in Table A.3.

Table A.3 Descriptive statistics for the continuous variables

	Mean	Std. Dev.	Min	Max	Number of observations
Model 1					
Temperature [°C]	0.05	2.97	-10	6	1 631
Walking speed [m/s]	1.40	0.26	0.48	2.17	1 631
Model 2					
Temperature [°C]	0.58	3.25	-6	5	472
Walking speed [m/s]	1.58	0.20	0.67	2.15	472
Model 3					
Temperature [°C]	-0.38	3.64	-6	5	395
Walking speed [m/s]	1.45	0.16	0.91	1.98	395

The descriptive statistics for the factor variables in Model 1-3 are presented in Table A.4.

Table A.4 Descriptive statistics for the factor variables. Number of observations for each category of the factor variables in % and the absolute values in parentheses

Model 1						
Surface condition	Asphalt	Compact snow	Loose snow	Gritted ice	Ice	Total
	28.14	26.79	16.86	9.63	18.58	100
	(459)	(437)	(275)	(157)	(303)	(1 631)
Age	Younger	Middle-aged	Older	Total		
	40.83	32.43	26.73	100		
	(666)	(529)	(436)	(1 631)		
Sex	Female	Male	Total			
	53.34	46.66	100			

	(870)	(761)	(1 631)			
Crampons	Did use	Did not use	Total			
	2.08	97.92	100			
	(34)	(1 597)	(1 631)			
Stroller	Did use	Did not use	Total			
	1.66	98.34	100			
	(27)	(1.604)	(1 631)			
Walker	Did use	Did not use	Total			
	2.51	97.49	100			
	(41)	(1 590)	(1 631)			
Model 2						
Surface condition	Asphalt	Compact snow	Loose snow	Gritted ice	Ice	Total
	23.94	18.43	1.27	45.34	11.02	100
	(113)	(87)	(6)	(214)	(52)	(472)
Age	Younger	Middle-aged	Older	Total		
	76.27	23.09	0.64	100		
	(360)	(109)	(3)	(472)		
Sex	Female	Male	Total			
	45.55	54.45	100			
	(215)	(257)	(472)			
Crampons	Did use	Did not use	Total			
	1.69	98.31	100			
	(8)	(464)	(472)			
Model 3						
Surface condition	Asphalt	Compact snow	Loose snow	Gritted ice	Ice	Total

	22.78 (90)	40.76 (161)	8.35 (33)	26.58 (105)	1.52 (6)	100 (395)
Age	Younger	Middle-aged	Older	Total		
	72.91	26.08	1.01	100		
	(288)	(103)	(4)	(395)		
Sex	Female	Male	Total			
	48.61	51.39	100			
	(192)	(203)	(395)			
Crampons	Did use	Did not use	Total			
	0.51	99.49	100			
	(2)	(393)	(395)			

Table A.5 shows the summary statistics of walking speed in Models 1-3.

Table A.5 Summary statistics for walking speed

Summary statistics walking speed [m/s]	Model 1 (whole sample)	Model 1 (when the older pedestrians are omitted)	Model 2 (whole sample)	Model 3 (whole sample)
25th percentile	1.247	1.373	1.446	1.342
50th percentile	1.442	1.502	1.584	1.455
75th percentile	1.581	1.623	1.716	1.559
Mean	1.398	1.494	1.581	1.452
Standard deviation	0.264	0.198	0.200	0.164
Variance	0.070	0.039	0.040	0.027
Skewness	-0.591	-0.333	-0.139	-0.021
Kurtosis	3.285	3.882	3.687	3.161
Number of observations	1 631	1 195	472	395

Appendix B – Regression diagnostics

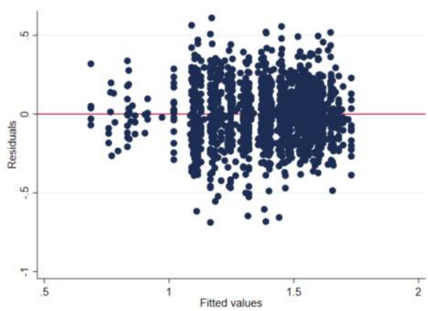
One assumption for OLS regression is that there is no multicollinearity between the independent variables in the regression model. Table B.1 shows the variance inflation factors (VIFs) in the three models. VIF values below 3 are regarded as acceptable (Hair et al., 2019). Multicollinearity does not seem to be a problem in any of the models.

Table B.1 Variance inflation factors (VIFs)

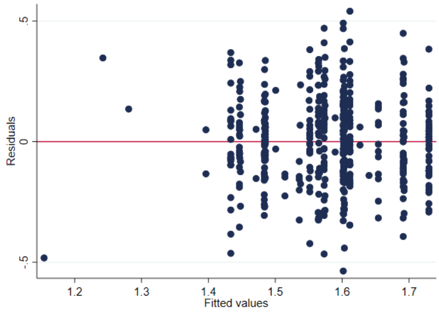
	Model 1	Model 2	Model 3
Temperature	1.26	1.56	1.32
Surface condition			
Compact snow	1.79	1.84	1.67
Loose snow	1.40	1.09	1.32
Gritted ice	1.27	1.90	1.89
Ice	1.45	1.37	1.07
Sex	1.01	1.03	1.01
Age			
Middle-aged	1.29	1.09	1.04
Older	1.41	1.01	1.01
Crampons	1.05	1.08	1.02
Stroller	1.03	-	-
Walker	1.08	-	-
Mean VIF	1.28	1.33	1.26

To investigate whether the models show any evidence of heteroscedasticity, we have plotted the residuals with their fitted values in Figure B.1.

Model 1:



Model 2:



Model 3:

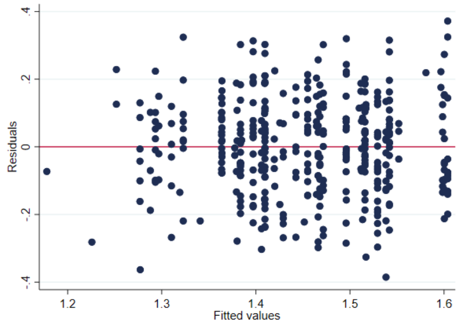


Figure B.1 Residual-versus-fitted plots

The plots show some heteroscedasticity in Model 1, while heteroscedasticity does not seem to be present in Model 2 and Model 3. Heteroscedasticity does not affect the estimates of our coefficients but can affect the estimates of the standard errors. One standard solution to deal with heteroscedasticity is to use robust standard errors in the models. This option relaxes the assumption that the errors are identically distributed (Mehmetoglu and Jakobsen, 2017). We have therefore re-estimated the models using standard errors that are robust to heteroscedasticity. As shown in Table B.2, this does not alter any substantial conclusions. The coefficients of our main independent variables are still statistically significant at the same level as before.

Table B.2 OLS models using robust standard errors to deal with heteroscedasticity

	Model 1	Model 2	Model 3
Temperature	-0.013***	0.000	-0.013
	(0.00)	(0.00)	(0.00)
Compact snow	-0.108***	-0.038	-0.064**
	(0.01)	(0.03)	(0.02)
Loose snow (2-8cm)	-0.133***	-0.102*	-0.110***

	(0.01)	(0.04)	(0.03)
Gritted ice	-0.151***	-0.127***	-0.097***
	(0.02)	(0.02)	(0.02)
Ice	-0.255***	-0.178***	-0.043
	(0.01)	(0.03)	(0.03)
Male	0.081***	0.118***	0.132***
	(0.01)	(0.02)	(0.01)
Middle-aged	-0.072***	-0.037	-0.087***
	(0.01)	(0.02)	(0.02)
Older	-0.351***	-0.449*	-0.290**
	(0.01)	(0.21)	(0.10)
Did use crampons	0.075	0.104	0.064
	(0.04)	(0.06)	(0.16)
Did roll a stroller	-0.095**	-	-
	(0.04)		
Did use a walker	-0.333***	-	-
	(0.02)		
Constant	1.600***	1.611***	1.469***
	(0.01)	(0.02)	(0.02)
Observations	1631	472	395
R^2	0.539	0.206	0.274

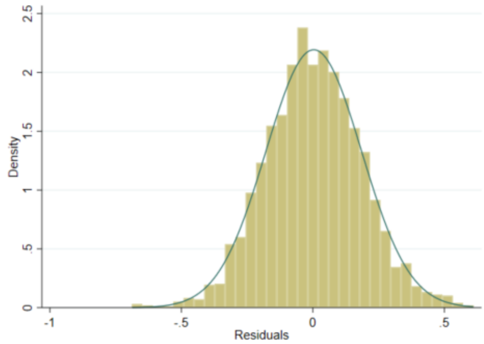
Base categories: Asphalt, Females, Younger pedestrians, Did not use crampons, Did not roll a stroller, Did not use a walker.

Robust standard errors in parentheses

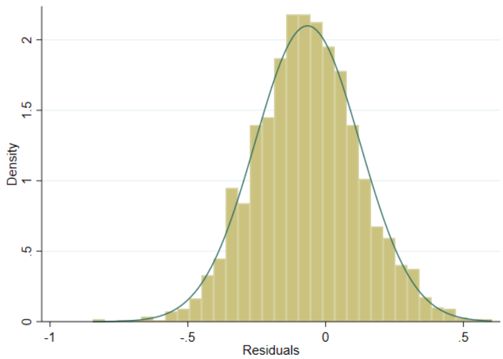
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

To investigate whether the residuals are normally distributed, we have plotted them in the histograms shown in Figure B.2. As seen, the residuals follow a normal distribution quite well.

Model 1:



Model 2:



Model 3:

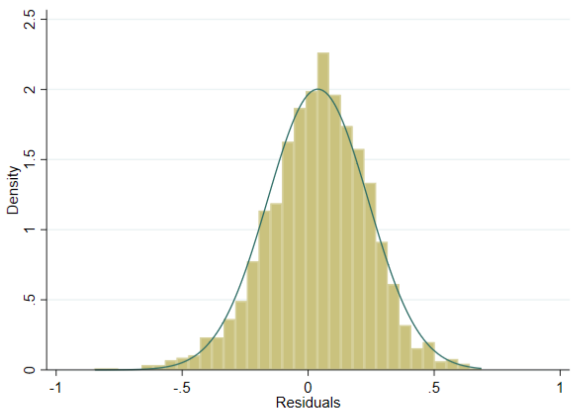


Figure B.2 Distribution of the residuals

Supplementary references

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D Paper IV

Pedestrians’ single accidents during winter conditions: An observational study

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Abstract

Background: Single accidents among pedestrians has high societal costs and are harming those who experience them. Despite this, studies focusing on single accidents among pedestrians are relatively few.

Objectives: Estimate the difference in pedestrians' single accident risk between some types of pavement surface conditions typically found in winter environments. Evaluate whether using "close calls" as an indirect measure of single accidents is appropriate for studying single accidents among pedestrians during winter.

Method: 2498 pedestrians were observed as they walked on sidewalks and walkways with different types of pavement surface conditions, and whether they experienced a close call, single accident, or not, was registered. The method was inspired by the Swedish traffic conflict technique.

Results: On homogeneous pavement surface conditions, given that close calls can be used as an indirect measure of single accidents, the results indicate that the single accident risk on gritted ice is approximately seven times greater, and on clean ice 14 times greater, than on compacted non-slippery snow. Hence, the risk of single accidents can be halved by gritting an ice-covered pavement. The results also indicate that "hot spots," meaning particularly slippery spots surrounded by non-slippery conditions, are a likely cause of many single accidents during winter. However, the method used in the current study has some limitations that must be addressed in future research.

Introduction

Single accidents among pedestrians during winter is a serious problem harming those affected and causing huge costs for society yearly. In Norway, approximately seven single accidents per 1000 inhabitants occur yearly (Elvik, 2019). This equals around 37 000 single accidents per year nationwide. Traditionally, single accidents among pedestrians have received little attention in the traffic safety literature. The main reason being that, unlike car and bicycle accidents, single accidents among pedestrians are formally not defined as traffic accidents because no moving vehicle is involved in such accidents. Putting the formal definition aside, the single accidents that occur in what we informally can think of as the traffic environment should be of interest to professionals working with traffic safety.

Despite that single accidents among pedestrians have received less attention in the literature than other types of traffic accidents, some studies have investigated the topic of single accidents in winter environments. In a review article on pedestrian falls, Schepers et al. (2017) identified 28 studies that included material relevant to pedestrian falls, 10 of these were from countries with cold winters. Seven of them paid attention to the risk of ice and snow on the ground.

Single accidents among pedestrians are way more frequent than pedestrian injuries in road traffic accidents (Schepers et al., 2017). A previous study analyzing hospital data of pedestrian injuries in Oslo found that among the 6309 reported accidents, 97 % were single accidents (Sundfør and Bjørnskau, 2016). The number of pedestrian accidents was found to be doubled during winter compared to summer, and most of the accidents during winter happened because people fell on ice and snow.

In a Swedish study of single accidents among pedestrians, Öberg (1998) found that pedestrians have six to eight times higher injury risk on snow- and ice-covered surfaces than in the summer. The author also found that, above all, slipping and falling on ice and snow is a problem among older people.

In a Swedish study investigating fall-related injuries among senior citizens, Gyllencreutz et al. (2015) found that environmental factors such as icy street conditions were the most common self-reported cause of the incidents that lead to injuries. They also found that the number of single accidents among the seniors was three times greater during the winter months (November to April) than in the other months of the year.

In another Swedish study, Berggård and Johansson (2010) found the risk of a single accident when walking on snow and ice to be about three times higher than walking on a bare pavement surface condition, when no anti-slip device is used. The authors did adjust for distance walked when obtaining this number. Those who used anti-slip devices experienced 36 % fewer falls per km walked; however, the difference was not statistically significant. They also found that the use of anti-slip devices increases the amount of walking. A similar finding, indicating an increased amount of walking when anti-slip devices are used, was reported by Mckiernan (2005).

Common for most of the reported studies is that they categorize the surface conditions dichotomously. On the one side, it is the bare pavement condition, and on the other, a pavement covered with snow or ice, or the distinction is drawn between summer and winter. This approach has its purpose, especially for large sample studies and general trends. The apparent reason why they make this dichotomization is that the data is collected from hospitals or self-reporting. Therefore, more specific descriptions of the pavement surface conditions where the accidents occurred can be difficult to determine after. At best, one can expect to have a general description like “slippery ice” or similar, and a detailed time when the accident occurred. However, this approach is not as practical if winter operation measures other than providing bare pavement surfaces are evaluated. For instance, it is interesting to know the expected safety gains by gritting ice-covered pavements and identify the safety performance of high-standard snow-covered pavement surfaces compared to sub-optimal conditions.

Scope of the research

The aim of this paper is twofold. Firstly, to estimate the difference in pedestrians’ single accident risk between some pavement surface conditions typically found in winter environments. Secondly, to evaluate whether using “close calls” as an indirect measure of single accidents is appropriate for studying single accidents among pedestrians during winter.

Definitions

In this paper, a *close call* is defined as a pedestrian skidding and clearly losing balance but avoids falling to the ground by regaining control of the situation. In other words, the pedestrian is about to fall but does not. On the other hand, a *single accident* is defined as a pedestrian skidding and falling to the ground.

Close calls as an indirect measure for single accidents

The inspiration for using close calls as an indicator or indirect measure for single accidents was found in the Swedish traffic conflict technique (Sakshaug et al., 2013; Laureshyn and Várhelyi, 2018). Ideally, actual single accidents should be used to assess the accident risks of various pavement surface conditions. However, this approach has some serious limitations. Accidents in traffic are rare events and collecting enough data to produce reliable estimates of accident risks would be very time-consuming. Further, traffic accidents are random events. The number of accidents registered each year at the same place cannot be expected to be consistent, even if the winter operation level of service is equal from year to year. Therefore, “the expected number of accidents” is a more factual estimate of the safety characteristics than the actual accident numbers themselves, which, seen this way, is an indirect measure (Laureshyn and Várhelyi, 2018). The expected number of accidents cannot be measured directly but only estimated using accident data and other measures (Hauer, 1997). Using reported accidents from hospital data have the limitation that not all accidents are reported.

For these reasons, the Swedish traffic conflict technique argues that an indirect measure is necessary for assessing traffic safety. By indirect, we mean a measure not based on accidents directly but on occurrences in traffic that are causally related to accidents or injuries (Laureshyn and Várhelyi, 2018). The idea is that such an indirect measure can indicate safety performance and help identify and understand processes that lead to accidents. Based on this, we wanted to use close calls as the indirect measure because we reasoned that close calls are causally related to actual single accidents and that they occur way more often than single accidents. In contrast to how this method often is applied, namely, to identify the safety performance of a particular place or location, we are interested in the safety performance of pre-defined types of pavement surface conditions that are typical during winter. The goal is to use close calls to estimate the relative difference in accident risk between these pavement surface conditions.

We have identified two studies where a similar method was applied (Öberg et al., 1996; Sakshaug et al., 2013). In the study conducted by Öberg et al. (1996), they gathered the data from video recordings rather than by an observer in the field. They concluded it was difficult to extract near-accidents from the videos. On the other hand, Sakshaug et al. (2013) collected the data by manual observations. They concluded that the method was applicable but rather resource intensive. Their aim was to identify the accident risks on specific places in two Swedish cities based on where reported single accidents had occurred in the past. Their main conclusions were that paying attention to slippery surfaces and careful walking is not sufficient to avoid single accidents due to snow and ice. In part, this seemed to be due to the risk with ice on a walkway, especially on a slope, was underestimated by younger pedestrians while older pedestrians were more careful when it was slippery. Even when the pedestrians were watching closely, they did not detect the danger in the form of ice under snow and hard ice and snow edges. Very few took advantage of the opportunity to take a small detour to walk on bare ground instead of ice coated surfaces. The authors stated that many people did not seem to take the risk of a single accident so seriously. Six out of seven near-accidents in the city of Gothenburg occurred on a couple of patches of ice, at small irregularities in the surface, caused by polishing due pedestrians having walked over it repeatedly.

Methods

Data collection

The data was collected in Trondheim, Norway, during the winter of 2019/20. The data was collected by manual observations of pedestrians walking naturalistically, without being aware that they were being observed. The observer was registering pedestrians as they walked a distance with a predefined start- and endpoint. The pedestrians were registered as either walking normally or experiencing a close call or a single accident. The time they spent walking the distance, and the number of steps they used were also registered simultaneously. The results from these analyses are published separately (Fossum and Ryeng, 2021, Fossum et al., forthcoming). The severity of the accidents is not considered in the observed data that are analyzed.

The observations were conducted on weekdays in four different neighborhoods. The neighborhoods were chosen due to demographic characteristics of the people usually walking there and the pavement surface conditions we could expect there during the winter, based on previous experience. We did not choose the sites for the data collection based on previously reported accidents or similar. One observer did all the registrations and measurements. The time spent observing was unfortunately not registered. A conservative estimate of the time spent collecting the data is 70 hours (observation time), not including the time used for reconnaissance and planning.

In total, 2498 pedestrians were registered. Of these, 51.1 % were women. The age and gender of the pedestrians were determined by observation. Therefore, the age categorization is approximate rather than definitive. The age distribution was 17.7 % older people, 52.6 % were younger (between 18-30 years old), and 29.7 % were middle-aged. 65.3 % of the observations were conducted on flat ground, while the remaining were on a walkway with an inclination of approximately 8 %. Their distribution on the various types of pavement surface conditions is shown in Table 1.

Pavement surface conditions (PSC)

In this study, we have differentiated between the following types of pavement surface conditions (PSCs): Asphalt, Compact snow, Loose snow, Gritted Ice, and Ice. The PSCs described below had to be homogenous, covering the whole walking path between the start- and endpoint.

For any PSC to be classified as "Asphalt," the requirements were that it had to be clean asphalt, without any snow, ice, gravel, or any other medium above the pavement.

For any PSC to be classified as "Compact snow," the requirements were that the surface had to be a compacted rough snow layer without any medium above the compacted snow (except grit) and any ice formation or polishing of the surface. In practice, the surface had to have relatively high available friction.

A PSC classified as "Loose snow" had a snow depth between 2 to 8 cm, and the loose snow had to be above an asphalt pavement or compacted snow. We did not allow ice to be present beneath the loose snow. The 2-8 cm range was not a requirement, but we did not have observations on deeper snow than this.

A surface of polished compact snow or ice that had been gritted was classified as "Gritted ice."

The PSC classified as "Ice" was an ice layer without any medium above the ice. Illustrations and more in-depth descriptions of the PSC can be found in Fossum and Ryeng (2021).

Restrictions in which data that were registered

We did not record all close calls we observed while collecting the data. One of the criteria for recording any close call was that they occurred between the predefined start- and endpoint. The second criterion was that the time-measuring[8] of the pedestrian experiencing the close call had started before the close call occurred. The second criteria ensured that the pedestrian experiencing the close call would have been included in the dataset even if they had not experienced the close call, thereby providing the possibility to reasonably indicate a measure of exposure. Ideally, exposure to risk should be measured by distance walked (Elvik and Bjørnskau, 2019). However, due to the research design, this was not possible in the current study.

Even though the main purpose of the data collection was to gather data on close calls as an indirect measure of single accidents, we did also register single accidents we observed. We deemed it unreasonable not to register actual single accidents in a study on single accidents among pedestrians, even when the chosen method clearly stated that close calls would be used as an indirect measure of single accidents.

Since actual single accidents are rare incidents, we were not as strict in which single accidents we registered. We did register all single accidents observed while collecting the data, no matter where they occurred. The single accidents could happen anywhere in sight and were registered if the observer detected them. For this reason, it is not possible to assess the exposure in the data of observed single accidents. When a single accident occurred, a description of the spot where it happened was immediately written down with other relevant information like the person's approximate age, gender, and the

[8] This is thoroughly described in Fossum and Ryeng (2021)

sequence of events. A qualitative approach was used in the analysis of the single accidents.

Since the single accidents could happen anywhere and still be registered, the strict categorization of the pavement surface conditions where we registered the close calls was not complied with for the single accidents. We will, therefore, use the term "perceived pavement surface condition" while describing the PSC where the single accidents occurred. "Perceived," meaning which PSC it was most similar to of the described PSCs, but still would not have been classified as such in the analyses of the close calls. They would not have been classified as such because the PSC were not homogenous where the single accidents occurred, which will be discussed in the review of the results.

Accident risk and rate of close calls

Because of the research design, the distance traveled by any of the pedestrians was unknown. By accident risk we mean the probability to be involved in an accident per distance traveled in traffic (Høye and Elvik, 2019). Ideally, a standard measure of single accident risk on pavement surface condition (PSC) x can look like:

$$Single\ accident\ risk\ (PSC\ x) = \frac{Number\ of\ single\ accidents\ (PSC\ x)}{Distance\ walked\ by\ pedestrians\ (PSC\ x)}$$

Since the walked distance is not known and we use close calls as an indirect measure of single accidents, our simplified measure of "single accident risk" – which more correctly should be referred to as the rate rather than the risk – on pavement surface condition x using close calls as an indirect measure, is:

$$Rate\ of\ close\ calls\ (PSC\ x) = \frac{Number\ of\ close\ calls\ (PSC\ x)}{Total\ number\ of\ observed\ pedestrians\ (PSC\ x)}$$

This expression does not calculate the risk of single accidents but rather the rate of close calls. The abbreviation RCC will be used for the rate of close calls. If the assumption that close calls and single accidents are causally related is valid, RCC can be used to evaluate the relative safety performance of the investigated pavement surface conditions.

Results and discussion

Close calls

Figure 1 shows the number of observed close calls on each type of pavement surface condition analyzed. In Table 1, we have calculated the RCC on each type of pavement surface condition we investigated.

Figure 1 Observed close calls on each type of pavement surface condition

The general trend is that the accident risks increase as the slipperiness of the pavement increases, as one would intuitively expect. On loose snow and asphalt, we did not observe any close calls. This does, of course, not mean that the risk is zero. If the observational period had been extended, close calls on all pavement surface conditions would have occurred. However, it gives an impression of the relative risk between the other PSC when compared. On non-slippery compact snow, the calculated RCC is 0.4 %. On gritted ice and ice, the calculated RCCs are 3 % and 6 %, respectively.

Table 1 Rate of close calls (RCC) on each type of surface condition based on the number of close calls related to the total number of observations

Pavement surface condition	Number of pedestrians	Number of close calls	Rate of close calls (RCC)
Asphalt	662	0	0 %
Loose snow	314	0	0 %
Compact snow	685	3	0.44 %
Gritted ice	476	14	2.94 %
Ice	361	22	6.09 %
Total	2 498	39	1.56 %

To test whether the differences in RCC on compact snow, gritted ice, and ice is random or not, we ran a Fisher-Freeman-Halton exact test on the 3x2 matrix containing close calls. The test statistic is 31.460 ($p<0.000$), indicating that the reported associations are nonrandom.

The accident risk cannot be deduced from the RCC directly; it is substantially lower, but how much is unknown and can only be estimated using alternative measures. However, if the assumption that close calls and single accidents are causally related is valid, we expect the relative difference in single accident risk and RCC between the different PSCs to be equal. This means that, based on Table 1, the accident risk on gritted ice is approximately seven times greater than on compacted non-slippery snow. On clean ice, the accident risk is 14 times greater than on compacted non-slippery snow. It is also worth noticing that according to the data, the risk of single accidents can be halved by gritting an ice-covered pavement.

Since the number of close calls is relatively few, any quantitative analysis like binary regression or similar is not very meaningful. However, it might be worth noticing that 23 of the close calls occurred on flat ground and the remaining while walking on a downward slope. Only two of the close calls involved older pedestrians. All close calls involved pedestrians who were not using any anti-slip device, indicating that there is a potential to prevent single accidents by using such devices.

Single accidents

In total, 11 single accidents were observed in the observational period this winter. Eight of them occurred on a type of pavement surface condition, most likely perceived as compact snow, one on perceived loose snow, and two on gritted ice (see Figure 2). The common feature between all the observed single accidents was that the pavement surface conditions were not homogenous where they occurred. All single accidents occurred on a particularly slippery spot, surrounded by non-slippery surface conditions. For this reason, the perceived pavement surface condition is a description of the surrounding surface conditions of where the accidents occurred.

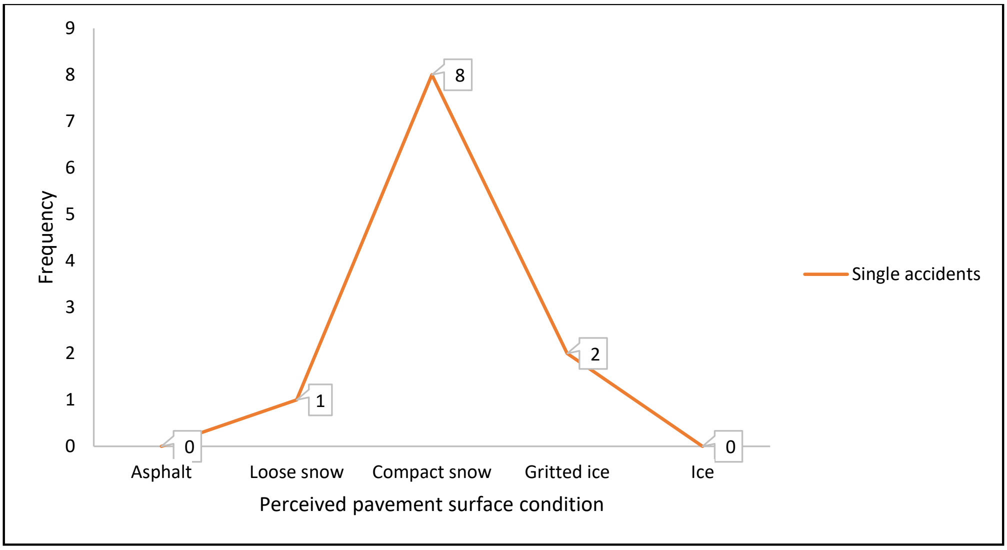

Figure 2 Observed single accidents on pavement surface conditions perceived like those in Figure 1

One middle-aged female pedestrian slipped and fell on clean ice hidden under loose snow. The pedestrian was walking on a sidewalk, and the snow depth was 10 cm. The ice under the snow did not cover the whole sidewalk but was only present at the spot where she fell.

Two older female pedestrians slipped and fell on a gritted ice pavement. The two fell on the exact same spot. The spot where they fell was more polished and slippery due to less gritting where they slipped than the surrounding area. The walkway where the two fell had a minor inclination, and they were walking in the downwards direction.

Four single accidents occurred on a spot when walking downwards on a walkway with an 8 % slope on a perceived compact snow surface. The spot where they fell was polished and had almost turned to ice. The surrounding areas, on the other hand, were of compact snow with high available friction. Two of the pedestrians were younger men, one was a young woman, and the last was a middle-aged man. One single accident occurred on the same walkway with an 8 % slope, but at a different spot where the superelevation of the walkway was steeper than the rest of the walkway. The pedestrian who fell was a middle-aged man who seemed to walk very cautiously prior to the fall. Three single accidents occurred on a non-gritted compact snow pavement when walking downwards on the opposite side of the roadway from where the above five described accidents on perceived compact snow occurred. They were two younger men and one younger woman. The single accidents described in this paragraph happened on the same day. It is worth noticing that when observations were conducted the day after, the walkways had been gritted. We did not observe any single accident during a two-hour observational period after the pavements were gritted.

Evaluating the method

There are two main reasons the methodology of the current study can be considered inappropriate. First, based on the data, it is not evident that there is a causal relationship between close calls and single accidents. If such a causal relationship exists, the shape of the curves in Figure 1 and Figure 2 would be similar, but with the curve showing the single accidents being substantially lower than the one showing close calls. This can be explained by the research design. All observed single accidents happened on what we can characterize as "hot spots," namely a particularly slippery spot surrounded by non-slippery pavement surface conditions. On the other hand, due to the requirement of the homogeneous pavement surface conditions where we observed the close calls, none of the close calls occurred on hot spots. The close calls and single accidents observed in this study are therefore not directly comparable.

If hot spots substantially contribute to single accidents during winter, evaluating accident risks on homogeneous pavement surface conditions cannot capture these accidents. However, even if many single accidents occur at hot spots, many likely occur on homogeneous pavement surface conditions as well. Given that there is a proportional relationship between the occurrence of close calls and single accidents, the RCC can be used to evaluate the risk of these accidents using the approach in the current study, keeping in mind that they do not tell the whole story of single accidents in winter environments.

Another possible explanation why there might not be a causal relationship is because pedestrians walk more cautiously on known slippery surfaces (Fossum et al., forthcoming). They walk with better stability and are likely more aware of the walking task. Pedestrians walk less cautiously on seemingly non-slippery pavement surface conditions. They might, therefore, be taken by surprise when they hit a slippery spot and have fewer capabilities to avoid falling to the ground. Following this line of thought, the accident reduction caused by improved winter operations and maintenance will likely be negatively affected because of behavioral adaptations. The reason being that pedestrians walk less cautiously on seemingly good pavement surface conditions. Another indication of a non-causal relationship is that so few older pedestrians were involved in the close calls. Only 5 % of the close calls involved older pedestrians, who in comparison constitute 18 % of the sample. This seems illogical considering older people are the most likely victims of single accidents on slippery surfaces (Öberg, 1998). A plausible explanation why so few older pedestrians were involved in the close calls are that they walk more cautiously on known slippery surfaces than younger pedestrians. Sakshaug et al., (2013) found older pedestrians to walk more cautiously in terms of taking detours to walk on less slippery ground. However, as indicated by Fossum et al. (forthcoming), in terms of walking behavior measured by step lengths and step frequencies on slippery surfaces, older pedestrians do not seem to walk more cautiously than others.

Second, the time spent collecting the data was extensive. If the estimated 70 hours of observation time is correct, it took approximately 1.8 hours, on average, to observe one close call. Suppose a similar method should be tried in the future. In that case, it is highly advised to use a semi-automatic method like video recordings with manual extractions of the data or similar, rather than manual observations. Video recordings were not used for the current study because other data were collected simultaneously as well. For these data, it was deemed more appropriate to use manual observations.

Recommendations

It might be difficult to predict where the hot spots are formed, which also has implications for mitigating them. For practical purposes, a reactive approach can turn hot spots cooler. If hospitalized pedestrians who have suffered injuries due to single accidents can localize and pinpoint the spot where the fall occurred on a map, this information should immediately be communicated to the winter operation personnel and the road owners. The spots can thereby quickly be secured by, for instance, gritting or scraping, before any more pedestrian's experience falls on the same spots.

A more proactive approach is to investigate how hot spots are formed. Even if they might be very local, weather forecasts can tell when they likely will be formed if their preconditions are known. In addition to actively securing known hot spots, specific winter operation measures can be implemented on prioritized segments of the road network when there is reason to believe that the pavement surface conditions will turn particularly slippery. The approach of Ruotsalainen et al. (2004) is promising in this regard. That a substantial amount of single accidents happen after specific weather events was also reported in a Canadian study (Morency et al., 2012). They found that three episodes of excess single accidents were preceded by rain and followed by falling temperatures or were concomitant with freezing rain. The number of single accidents during these days was almost three times higher than the average during the same winter months. Such results highlight the importance of the proactive approach to mitigate single accidents during winter.

A general approach is to provide an increased number of bare asphalt pavements during winter, especially on prioritized parts of the road network. Since older pedestrians are most affected by slippery conditions in terms of single accidents (Öberg, 1998), and many older people are reluctant to walk outside if the street conditions are poor (Rantakokko, 2009), neighborhoods inhabited by many older people and their surrounding areas, perhaps, should be prioritized when deciding winter operational levels of service to mitigate single accidents. The individual responsibility of using anti-slip devices or suitable footwear to prevent accidents on slippery pavement surface conditions is also of great importance.

Limitations and future research

The biggest limitation of the conducted study is the amount of data. The 39 close calls and 11 single accidents that were observed are insufficient to conduct any quantitative analyses, and it also makes the obtained RCCs uncertain. More data is needed if the RCCs should be used to accurately estimate the relative safety performance of various pavement surface conditions typically found in winter environments. More data would have enabled more sophisticated analyses and made it possible to identify who is likely to experience single accidents. The limitations of the research design itself have been discussed.

An interesting approach for future research is to interview people at hospitals immediately after they have experienced a single accident. The respondents should be asked to pinpoint the location where the accident happened on a map, and the researcher should then inspect the location and identify common characteristics of the pavement surface conditions of where the accidents occur. The respondents should also be asked about behavior prior to the incident to identify common behavioral characteristics causing single accidents. By this approach, much can be learned about preconditions for single accidents during winter and help identify useful and specific measures to mitigate them.

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