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

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A R T I C L E I N F O

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A B S T R A C T

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.

1. 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.

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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 15th-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, 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. 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:
  o Asphalt.
  o Compact snow.
  o Loose snow.
  o Gritted ice.
  o 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.

Fig. 1. Surface conditions categorized as “Asphalt”.

Fig. 2. Surface conditions categorized as “Compact snow”.

- 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.

Fig. 3. Surface conditions categorized as “Loose snow 2–8 cm”.

Fig. 4. Surface conditions categorized as “Gritted ice”.

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

Fig. 5. Surface conditions categorized as “Ice”.

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 and 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. Pictures of the different surface conditions are shown in Figs. 1–5.

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.

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

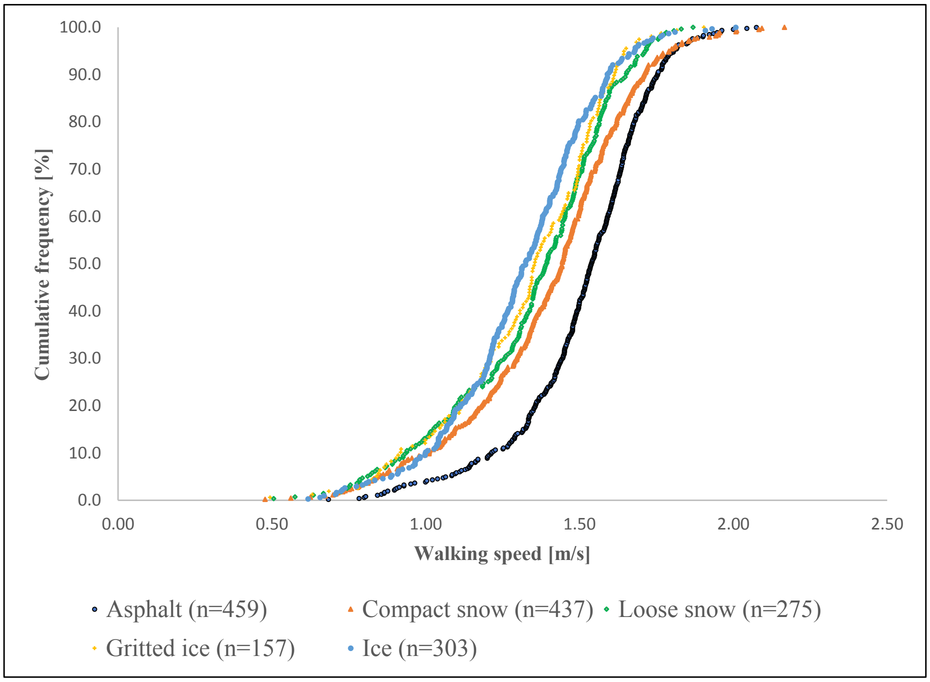

Fig. 6. Empirical CDFs for walking speed on the different pavement surface conditions on flat ground.

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.

2.3.3. Loose snow

To be classified as "Loose snow 2–8 cm", the whole surface where the measurements were conducted had to be loose snow with a snow depth between 2 and 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

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	Model 2	Model 3
	Walking speed [m/s] (Flat ground)	Walking speed [m/s] (Slope = -8%)	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 (2–8 cm)	−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
* $p < 0.05$,
** $p < 0.01$,
*** $p < 0.001$

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.

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 Fig. 4. In other words, this category can be regarded as the intermediate state between what we have classified as compacted snow and 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.

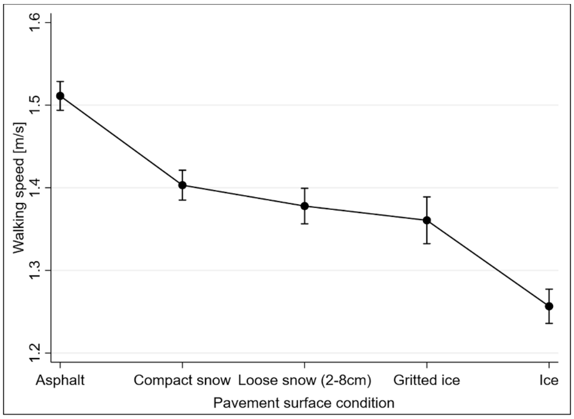

Fig. 7. Predictive margins of surface condition with 95% Confidence intervals, calculated from Model 1.

3. 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.

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 Fig. 6. From Fig. 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.

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.

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.

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.

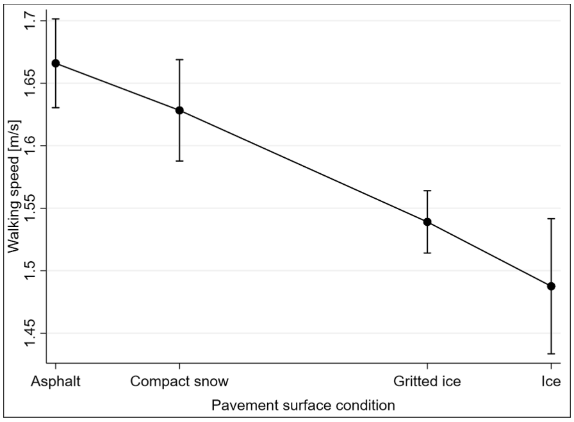

Fig. 8. Predictive margins of surface condition with 95% Confidence intervals, calculated from Model 2.

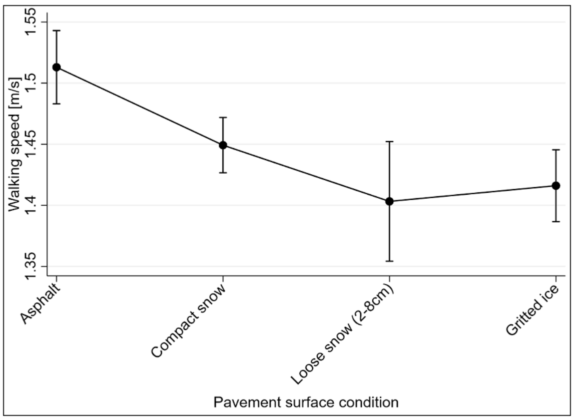

Fig. 9. Predictive margins of surface condition with 95% Confidence intervals, calculated from Model 3.

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 and 15 °C = 1.40 Temperatures between 15 and 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 ages under different environmental conditions	Manual recording using a stopwatch	Yes	Somewhat	There is a significant negative relationship between air temperature and walking speed In general, faster walking speeds during weather conditions categorized as "snow" than "dry"*	Younger pedestrians "dry" = 1.47 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

(continued on next page)

Table 4 (*continued*)

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]
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 real-life environment	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
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	Median comfortable walking speed baseline = 1.39 Median maximum walking speed baseline = 1.92
					On snow-covered ice, the speed was significantly reduced for one device	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 walking speed during winter	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 "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.

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 and 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.

Fig. 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 and 8 cm and gritted ice is significantly different from the walking speed on compact snow.

Using the walking speeds calculated in Model 1 and shown in Fig. 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>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 asphalt. The predictive margins of surface conditions on walking speed for walking downwards on a slope of −8% are presented in Fig. 8.

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 Fig. 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 Fig. 9.

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.

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 s on compact snow to 16 s on ice). However, as expected, the average walking speeds increased when we removed this age group from the analysis.

4. 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 min 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).

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 s 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 s 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 min.

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. 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.

CRediT authorship contribution statement

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

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Appendix A. – Model variations and descriptive statistics

Table A1 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.

In Table A2, 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 A2, all observations on flat ground are included, while the second column shows the

Table A1
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 (2–8 cm)	−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
* $p < 0.05$, ** $p < 0.01$,
*** $p < 0.001$

Table A2
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	Walking speed
	[m/s]	[m/s]
	All observations on flat ground	When the older age group is omitted from the analysis
Constant	1.603***	1.605***
	(0.02)	(0.02)
Temperature	−0.013***	−0.014***
Compact snow	(0.00)	(0.00)
	-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.
* $p < 0.05$,
** $p < 0.01$,
*** $p < 0.001$

Table A3
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

Table A4
. 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	40.76	8.35	26.58 (105)	1.52	100
	(90)	(161)	(33)		(6)	(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 A5
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

results when the older pedestrians are omitted from the analysis.

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 A3.

The descriptive statistics for the factor variables in Model 1–3 are presented in Table A4.

Table A5 shows the summary statistics of walking speed in Models 1–3.

Appendix B. – Regression diagnostics

One assumption for OLS regression is that there is no multicollinearity between the independent variables in the regression model. Table B1 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.

To investigate whether the models show any evidence of heteroscedasticity, we have plotted the residuals with their fitted values in Fig. B1

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 B2, this does not alter any substantial conclusions. The coefficients of our main independent variables are still statistically significant at the same level as before.

To investigate whether the residuals are normally distributed, we have plotted them in the histograms shown in Fig. B2. As seen, the residuals follow a normal distribution quite well.

Table B1
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

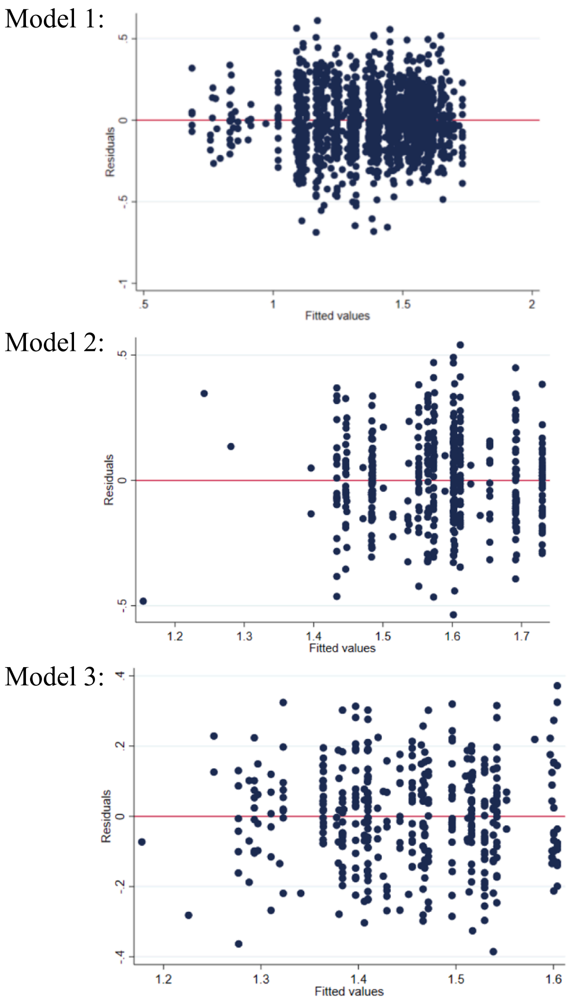


Fig. B1. Residual-versus-fitted plots.

Table B2
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 (2–8 cm)	−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)		

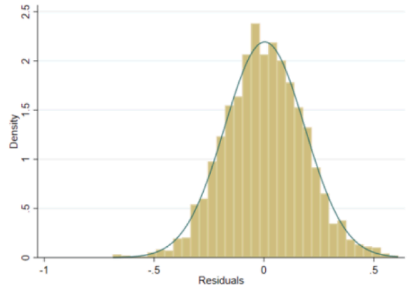
(continued on next page)

Table B2 (*continued*)

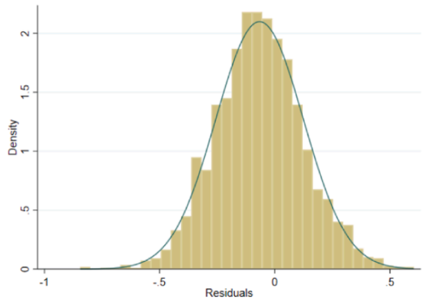
	Model 1	Model 2	Model 3
Did use a walker	−0.333***	–	–
	(0.02)		
Constant	1.600***	1.611***	1.469***
	(0.01)	(0.02)	(0.02)
Observations	1631	472	395
R^2	0.539	0.206	0.274

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

Model 1:



Model 2:



Model 3:

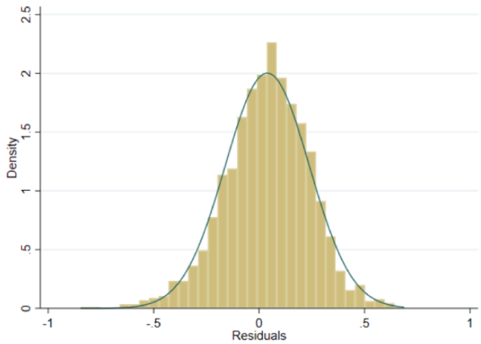


Fig. B2. Distribution of the residuals.

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