RoadSurf-Pedestrian: a sidewalk condition model to predict risk for wintertime slipping injuries

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Abstract
Icy and snowy sidewalks are typical wintertime phenomena in Finland. Wintertime slipping injuries are common and lead to substantial economic costs to health care as well as losses to society due to long sick leaves. In Finland, almost every second person slips and falls outdoors annually, and around 70,000 persons are injured needing medical attention. Typically, the most slippery conditions are encountered when the daily average temperature is slightly below 0°C or temperature crosses 0°C and there is precipitation in some form.

The Finnish Meteorological Institute (FMI) has developed a numerical weather model that simulates the level of slipperiness on the sidewalks. The model classifies the sidewalk slipperiness into three classes; normal, slippery and very slippery. The FMI issues warnings of hazardous sidewalk conditions to the general public. Pedestrians' road safety can be increased with sidewalk condition forecasts and warnings. When warned, people can choose proper footwear or use anti-slip devices, change the route or mode of transport, postpone the journey or cancel it altogether. Precise and reliable weather and sidewalk condition forecasts enable targeted and more effective sidewalk maintenance activities that can improve the grip of sidewalks and thus reduce the risk of accidents and injuries. This study presents the sidewalk condition model RoadSurf-Pedestrian, its physical principles and examples of model runs. There are some challenges in the modelling of the slipperiness but the model gives valuable information on the slipperiness for duty forecasters. Slipping injury statistics are also presented and used as verification data.

KEYWORDS
pedestrians, road safety, road weather forecasting, slipperiness, walking, weather warnings

1 | INTRODUCTION

Health impacts of weather and climate are of increasing concern due to the ongoing climate change and demographic changes such as ageing of the population that may increase vulnerability of people to weather related hazards. A hazard that has not been widely recognized is weather induced slippery sidewalk conditions in
wintertime leading to pedestrian slipping injuries. The number of yearly slipping injuries of pedestrians and cyclists needing medical attention is around 70,000; two-thirds of these occur in wintertime when the surface is icy or snowy (Grönqvist, 1995; Vuoriainen et al., 2000). Typical slip and fall injuries include bruises, sprains and fractures causing, at worst, long sick leaves and human suffering (Andersson and Lagerlöf, 1983; Lund, 1984; Strandberg, 1985; Björnstig et al., 1997; Eilert-Peterson and Schelp, 1998; Kemmlert and Lundholm, 2001; Flinckkilä et al., 2011). The annual costs of slip and fall injuries are estimated to be about €2.4 billion (2006 value) including the costs of medical care, loss of work input and reduced well-being (Hautala and Leviäkangas, 2007). Reduced well-being is estimated to account for 95% of the total costs. Slippery sidewalks can be hazardous also among tourists coming from places where they rarely, if ever, encounter snow, being thus unfamiliar and unprepared to face the Nordic winter environment (Lépy et al., 2016). In national risk and weather and climate risk assessments, wintertime pedestrian slipping injuries were recognized as a significant health risk in Finland (Tuomenvirta et al., 2018; Mol, 2019).

Northern high latitude countries have a distinct winter season or at least shorter cold periods with ice and snow. In Finland, the winter season is quite long, about 6 months, depending on the geological area. During this time ice and snow may exist on the ground, and the temperature is below or near 0°C. Coastal areas (about 10–20 km from the sea) may be substantially warmer and more humid than the inner part of the mainland (Pentti and Rovaniemi, 1994). Wintry conditions cause slipperiness and raise the risk of slip and fall among the people.

There is an evident causal relation between weather and pedestrians’ slip injuries. People can slip or fall throughout the year, but there is a clear seasonal variation; in wintertime the falls are more frequent and injuries more serious than during summertime. For instance, the number of fall related distal radius fractures is 2.5 times higher on slippery winter days compared to non-winter days (Flinckkilä et al., 2011). Similarly, a Russian study found that non-fatal accidental outdoor fall injuries were 1.7 times higher in the cold season compared to the warm season (Unguryanu et al., 2020). During winter, there are typically 5–20 days when the sidewalk conditions are very slippery with the number of slip injuries much higher than on average. Consequently, the workload in emergency rooms increases, especially due to leg and hand fractures. Previous studies have revealed that the number of slip injuries increases when the daily average temperature is slightly below 0°C, temperature crosses 0°C and/or there is precipitation in some form (Eskelinen, 1999).

When the significance of slipping injuries as a national health risk was realized, it was suggested that, with the help of a special weather service for pedestrians including warnings of slippery sidewalk conditions, the number of slipping injuries might be reduced (MTCF, 2005). During the winter 1998–1999, the Finnish Meteorological Institute (FMI) started a pilot service to warn pedestrians about slippery sidewalk conditions in the Helsinki metropolitan area. Later, starting from 2004, the service was expanded to cover the whole of Finland (Ruuhela et al., 2005). Evaluation of the service clearly indicated a need for new tools and education for forecasters as well as for further research on the dependence between slipping injuries and weather conditions.

In addition to the FMI, SVA-Konsultointi supplies warnings about slippery sidewalk conditions for several cities in Finland (http://liukastumisvaroitus.fi/index.php/en/home; Bezem, 2014). This service is based on observations. Worldwide, also, a couple of cities in other countries are, or have been, providing warnings of slippery sidewalk conditions for citizens. The city of Winnipeg launched a fall alert notification system to prevent wintertime falls in 2012 (Sylvestre, 2016). The service, called SureFoot, rated sidewalk condition into four classes from easy to hazardous. Another city with an information system for citizens about slippery sidewalk conditions is Sapporo in Japan. The service, called Walk Smart, provides tips for safe walking on snowy and icy roads as well as sidewalk slipperiness forecasts on the webpage http://www.tsurutsuru.jp/english/index_e.html (Kawamura et al., 2019). The service has been running since 2006 and it evaluates the expected slipperiness into three classes: “not slippery,” “slippery” and “extremely slippery.”

At the FMI, a road weather model RoadSurf has been developed to predict the road surface temperature, road condition and traffic index on roads (Kangas et al., 2015). As a tool for pedestrian warning, it has been further developed to predict the level of slipperiness on pedestrian sidewalks. Assisted by the modelled and forecasted slipperiness, FMI is issuing warnings when very slippery pedestrian sidewalk conditions are expected. The main aim of the present paper is to provide information on the RoadSurf-Pedestrian sidewalk condition model and its physical details with some examples of model runs. Furthermore, the needs for a targeted weather service for pedestrians and use of the model in an operational pedestrian warning service are discussed. Information about slipperiness and slipping injuries is also introduced as background information for the study.
2 | SLIPPERINESS AND SLIPPING INJURIES

2.1 | Slipperiness and friction

In this study, slipperiness means the friction, or grip, between surface and shoe sole. Physically, the friction coefficient is the ratio of the force required to move one surface over another to the total force pressing the two surfaces together (Weast, 1971). The friction coefficient $C_t$ is defined as the ratio of the horizontal friction force $F_\mu$ to the vertical (normal) force $F_n$ (Aschan et al., 2005):

$$C_t = F_\mu / F_n = (ma)/(mg) = a/g$$

where $m$ is the mass, $a$ the acceleration and $g$ the acceleration due to gravity. There are two types of friction coefficients: the coefficient of static friction is the ratio of the maximum static friction force between the surfaces in contact before movement commences, and the coefficient of kinetic friction is the ratio of the kinetic friction force between the surfaces in contact during movement.

Friction is a dimensionless coefficient which varies from 0 to 1, surfaces with lower values being more slippery than those with higher values, as presented in Table 1 (Grönqvist, 1995). Bare and dry asphalt has a good grip; water on the surface reduces friction a bit, snow and ice more. Most slippery sidewalk conditions during the winter develop when the temperature varies around 0°C, with melting and freezing cycles forming smooth icy surfaces, thus increasing the risk of slipping (Jylhä et al., 2009). Walking can be assumed to be safe if the friction coefficient is 0.2 or more (Ruuhela et al., 2005). In the case of running or when carrying load, a higher friction value is required.

Friction can be measured or estimated using several different instruments and methods. One type is a mechanical device based on braking and deceleration (Wallman and Åström, 2001) or on rotation of wheels (Malmivuo, 2016). Another type is an optical sensor that estimates the surface friction based on measured water/snow/ice layer information using spectroscopic measuring principles (Bridge, 2008; Vaisala, 2017). In addition to measuring devices, there are numerical models that use meteorological information (Juga et al., 2012) or neural networks and historical friction data (Pu et al., 2019) to predict the road surface friction.

The sensors and devices listed above have been developed to measure or estimate the friction between the road surface and vehicle tyre (Aschan et al., 2004). Unfortunately, most devices are not suitable for assessing slipperiness from the pedestrians’ point of view due to the fact that the parameters used differ too much from human biomechanical parameters (Chang et al., 2001a; 2001b). At present, there are no devices available that could measure operationally the slipperiness of sidewalks (Hippi, 2012).

The Finnish Institute of Health has developed a special portable slip simulator to measure the friction between road surface and shoe sole (Aschan et al., 2004; 2005). The portable slipmeter simulates stepping using the known force and step movement with different shoes attached to it. As a result, the instrument gives information about the prevailing friction between the shoe sole and the surface. The grip of the shoe is influenced by several sole properties, like sole material, hardness, roughness, wear, tread (geometry) design, centre of gravity and anti-slip devices (Grönqvist et al., 2001). The slipmeter gives a reliable estimate of the prevailing friction, but the device is intended for case studies and not for operational sidewalk slipperiness monitoring (Hippi, 2012).

2.2 | Data and statistics on slipping injuries

There are no complete statistics available about slip and fall accidents or injuries in Finland. There do exist some sources, however, from which slipping and falling accident and injury statistics can be collected, like the Finnish care register, ambulance transport, injury claim data or the injury databases of individual companies (Karlsson, 2013; Hippi et al., 2017). Accidents and injuries occurring to pedestrians and cyclists are typically single accidents (thus, without a collision with another party) and are not included in traffic accident statistics (Utriainen, 2020). Single accidents of these vulnerable road users are highly underreported (Airaksinen, 2018).

Slipping and falling injuries occur both indoors and outdoors throughout the year. In Finland, about 70,000 people are injured annually due to slipping or falling outdoors leading to serious consequences (Vuoriainen et al., 2000). Two-thirds of these injuries occur when the surface is covered by ice or snow (Grönqvist, 1995), which means about 50,000 slipping injuries during wintertime affecting about 1% of the Finnish population.

**TABLE 1** The connection between the coefficient of kinetic friction and subjective evaluations (Grönqvist, 1995)

| Class       | Explanation          | Coefficient of kinetic friction |
|-------------|----------------------|---------------------------------|
| 1           | Very slip-resistant  | ≥0.30                           |
| 2           | Slip-resistant       | 0.20–0.29                       |
| 3           | Unsure               | 0.15–0.19                       |
| 4           | Slippery             | 0.05–0.14                       |
| 5           | Very slippery        | <0.05                           |
Slips and falls occur on icy, snowy, slushy or frosty surfaces for both outdoor workers and the general public (Gao and Abeysekera, 2004). The winter months from November to March cover about 70% of the annual slipping and falling injuries, as will be presented later in the present study. The importance of choosing the right footwear is emphasized in slippery weather conditions. In very slippery sidewalk conditions, it is difficult to achieve adequate grip with footwear using a conventional sole structure. Therefore, in such conditions, it would be a good idea to use anti-slip devices or stud shoes (Hippi et al., 2017).

Slipping injuries can occur for everybody regardless of age and young people tend to slip more often than older people (Figure 1), but people between the ages of 35 and 65 are the ones who are most often injured and need medical attention (Figure 2) (Rantala and Pöysti, 2015). Slipping injuries are most harmful for elderly people because they may easily get hip or other fractures, and the consequences of the injuries are often more severe than among young people. Women over 50 years have the highest risk to slip and hurt themselves (Björnstig et al., 1997; Vuoriainen et al., 2000). According to a Swedish study, hospital stays caused by slipping are, on average, longer than for road traffic accidents (Björnstig et al., 1997).

Slips and falls often occur in familiar places, like on a sidewalk, outdoor path, courtyard or in parking places (Vuoriainen et al., 2000; Hautala and Leviäkangas, 2007; Rantala and Pöysti, 2015). Quite often slipping occurs as an unexpected sudden loss of grip when unexpected slipperiness is encountered (Grönqvist et al., 2001).

According to Pilli-Sihvola et al. (2019) the overall cost of slipping injuries is difficult to assess, as the injuries are not systematically recorded. In order to establish the overall harm, the patients and their recovery should be monitored for a long time after the incident. Assessing the decrease in work productivity is difficult, and various estimates are used in assessing the costs of lost well-being. Based on assessments used in the health sector, the annual direct and indirect costs amount to €420 million at national level (Vuoriainen et al., 2000). On the other hand, using the traffic sector’s figures, the same number of slipping injuries results in annual direct and indirect costs of €2.4 billion, including the costs of medical care (~€800 per fall), loss of work input (~€1,400 per fall) and reduced well-being (~€46,600 per fall) (Hautala and Leviäkangas, 2007). As can be seen, the major cost factor in this analysis is reduced well-being, accounting for about 95% of the total costs.

### 2.3 Commuting accidents

Most commuting accidents occur to pedestrians. In 2018, 57% of commuting accidents compensated to employees occurred to pedestrians, 23% to cyclists and 16% to car drivers or passengers (TVK, 2018). The driver or passenger of a car is interpreted as a pedestrian in the case of slipping or falling after leaving the car. 33% of commuting accidents occurred to men and 67% to women. According to surveys, women use cars less than men while commuting, which affects their risk of accidents (TVK, 2018).

In the present study, the slipping injury data in the Uusimaa region and in the whole of Finland in 2005–2018 obtained from the Finnish Workers’ Compensation Center (TVK) was used as an indicator for slippery conditions on sidewalks due to weather. The TVK coordinates the practical application of workers’ compensation. In Finland, the employers are obliged to insure their employees against work related accidents and injuries. The analysed data include injuries that have occurred while commuting and for which the insurance company has paid compensation from the occupational accident insurance. The TVK’s injury data are based on self-reported crashes that have been handled by the insurance companies, which have paid the compensation. Injury
descriptions have been written by the injured person, the supervisor, another employee or the claims handler in the insurance company (Utriainen, 2020). In this paper, a single-pedestrian injury is determined as an event when a pedestrian has slipped, fallen or stumbled. Henceforth, slipping includes fallings and stumblings when examining TVK’s slipping, falling and stumbling injuries.

Figure 3a presents daily numbers of slipping injuries on the way from home to work or vice versa in the Uusimaa region in 2010, based on TVK’s data, and Figure 3b shows the daily average air temperature measured at Helsinki Kumpula weather station. The Uusimaa region and Helsinki are presented on the map in Figure 4a,b. To get a more accurate estimation of the slippery days, some corrections have been made to TVK’s data (Karlsson, 2013). First, there is a clear day-of-the-week effect in the number of slipping injuries data because most people do not work and commute during weekends. The day-of-the-week effect is controlled by multiplying the number of slip injuries for each day by the weekday correction coefficient (Table 2). Second, since this study only concerns the injuries that occurred due to slippery sidewalk conditions, the injuries that occurred for other reasons are eliminated statistically. This is done by subtracting the average summertime (from May to October) daily injury amount (6.4) from all daily injury values. Occasional negative values produced by this correction method are set to zero. The temperature in Figure 3b is for Helsinki, but it serves as a good assumption for exposure because the population of Uusimaa is concentrated in Helsinki and especially the Helsinki metropolitan area.

The winter season, when the temperature is mainly below 0°C (blue background colour), can be clearly distinguished in Figure 3 with the number of daily slipping injuries being typically higher compared to the summer season (green background colour). There are 15–20 days each winter when the number of injuries is clearly higher than normal. The peak day of pedestrians’ slipping injuries is determined as a day when the number of

**FIGURE 2** Share of injured and those who needed hospital visits as a result of slipping and falling during 12 months by different gender and age classes based on a survey made by the Finnish Road Safety Council. Number of answers 644 (Rantala and Pöysti, 2015). See also Figure 1

**FIGURE 3** (a) Daily number of pedestrian slipping injuries on the way from home to work or vice versa in the Uusimaa region between January 1, 2010, and December 31, 2010. (b) Daily average air temperature observed in Helsinki Kumpula weather station in the same time period. Source of data: Finnish Workers’ Compensation Center (a), Finnish Meteorological Institute (b)
slipping injuries exceeds the threshold of the number with probability less than 0.01% in a Poisson distribution (Penttinen et al., 1998; Ruuhela et al., 2005). It can be assumed that the peak days are those with very slippery sidewalks.

According to TVK’s statistics there is a clear seasonality in the data, and the winter months from November to March cover 70% of the yearly slips (Figure 5). Summer months from June to August are underrepresented in TVK’s data due to the summer holiday season. There is also a substantial interannual variation in the injuries, as can be seen in Figure 6. This variation between the years is strongly related to slipperiness conditions during the years (TVK, 2018).

**TABLE 2** The correction coefficients for daily injury amounts when using the Finnish Workers’ Compensation Center data for each weekday in 2010 (Karlsson, 2013)

| Weekday  | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|----------|--------|---------|-----------|----------|--------|----------|--------|
| Coefficient | 0.6    | 0.8     | 0.8       | 0.9      | 0.9    | 5.4      | 6.2    |

**FIGURE 4** Map of Finland, with the Uusimaa region marked as red (a) and the city of Helsinki marked as red (b) (Wikipedia, 2020a; 2020b)

**FIGURE 5** The number of average monthly commuting accidents when the injured were walking. Data cover the whole of Finland, years 2005–2018 (TVK, 2020)
MODEL DESCRIPTION AND WEATHER WARNINGS

3.1 Road weather model RoadSurf

At the FMI, a road weather model RoadSurf has been developed (Kangas et al., 2015). Starting from 2000, RoadSurf has been used operationally to produce road weather forecasts and warnings for the Finnish road network. From 2004, an enhanced version of the model has been used to produce adverse weather warnings also for pedestrians on sidewalks (Ruuhela et al., 2005).

RoadSurf is a 1D energy balance model that calculates vertical heat transfer in the ground and at the ground–atmosphere interface, taking into account the special conditions prevailing at road or sidewalk surface. The effect of traffic is also accounted for. In order to quantify the hydrological state of the surface, the surface layer parameterization includes hydrological processes, such as accumulation of rain and snow, run-off of surface water, sublimation, freezing, melting and evaporation.

Depending on the nature of the surface, the model can be run in different modes, the main modes being car traffic and pedestrian sidewalk condition modes. A special mode for providing road surface maintenance advice has also been developed.

In all modes, in addition to calculating ground and surface temperature, RoadSurf makes a surface condition interpretation, describing the surface status using eight classes:

- dry
- damp
- wet
- frost (deposit)
- dry snow
- wet snow
- partly icy
- icy

The “partly icy” case means conditions in which only part of the surface, for example lanes with less traffic, is covered by ice. In this case the model also makes a secondary surface condition interpretation, which describes the surface in places where no ice is present. Similarly, the secondary surface condition class is used in cases with snow or water on top of ice.

The surface condition interpretation is based on various storage terms, which describe the amount of water, snow, ice and frost (deposit) on the surface. The model constantly tracks changes in the storages caused by melting, freezing, evaporation, condensation and mechanical wear. The storages may also interact with each other; for example, the size of the water storage is increased by precipitation as well as by melting of snow or ice.

RoadSurf also makes an overall classification describing the surface conditions in more general terms, telling whether the driving or walking conditions are normal or hazardous. This is done by combining the information about surface class with certain weather parameters (Kangas et al., 2015). This process is mode dependent, as for example difficult conditions for car traffic are not necessarily difficult for pedestrians, and vice versa (Ruuhela et al., 2005). A different classification is thus used in different RoadSurf modes (hereafter called RoadSurf-Traffic and RoadSurf-Pedestrian).

As input, output from a numerical weather forecast prediction model, either directly or with duty meteorologist’s corrections, is used as a forcing at the upper boundary in RoadSurf. This input also provides the horizontal coupling between individual points. The input variables include:

- ambient temperature
- relative humidity or dew point
- wind speed
- short wave solar radiation
- long wave solar radiation
- precipitation
- precipitation phase (optional)
The values of these variables can be taken from observations or from a forecast; the model does not make any distinction as to the source of the data. This makes it possible to run RoadSurf also for climatological research purposes. An additional forcing at the surface is the traffic, which causes not only increased turbulence (in the case of car traffic) but also mechanical wear of, for example, snow, ice or frost that is present on the surface. The details of the traffic influence are run mode dependent. At the lower boundary, sinusoidally varying climatological ground temperature is used as the boundary condition.

Starting from the forcing variables, the heat balance at the ground surface is then solved, taking into account such factors as sensible and latent heat flux as well as atmospheric stability. The effect of melting or freezing is also included in the energy balance. A more detailed description can be found in Kangas et al. (2015). Surface friction is also calculated using a statistical friction model that is based on observations from four Finnish road weather stations (Hippi et al., 2010; Juga et al., 2012).

As output, the model produces

- road (sidewalk) surface temperature,
- road (sidewalk) condition (primary and secondary),
- traffic (pedestrian) index,
- storage terms (amounts of water, ice, snow and frost on the surface),
- road surface friction (RoadSurf-Traffic only),

both in plain ASCII format and as a binary file for the GrADS (Grid Analysis and Display System) visualization program. The plain ASCII files can be used for further postprocessing, whereas GrADS is used to produce special graphical web pages.

In operational use, the initial state for the forecast is produced by running the model first for a few days using observations (initialization phase) and then continuing directly to forecast by changing the input from observations to forecast.

### 3.2 Pedestrians’ sidewalk condition model

The pedestrian sidewalk condition model (RoadSurf-Pedestrian) that is used to predict the level of slipperiness on the pedestrian sidewalk is physically the same as the RoadSurf-Traffic for car traffic, and is included as a separate mode in the same RoadSurf code base. The same data input is used in both modes. However, there are four main differences between RoadSurf-Traffic and RoadSurf-Pedestrian modes:

1. Traffic (pedestrians versus cars) and its effect on the road surface and storages are much lighter in RoadSurf-Pedestrian than in RoadSurf-Traffic.
2. Warning classification: circumstances producing hazardous conditions are not the same for car traffic and pedestrians.
3. Initialization phase: 96 hr in RoadSurf-Pedestrian versus 48 hr in RoadSurf-Traffic.
4. Because there is no information about the real initial state of the sidewalk surface conditions, two optional versions of the pedestrian forecasts are calculated, starting from different initial states: one with a layer of ice (30 mm) and another with no ice. Based on the expert judgement on the prevailing slipperiness situation, a user (meteorologist on duty) chooses the better initial state and thus the forecast version. Typically, during the winter season when there is snow and ice on the ground the initial state with ice is suitable, whereas in autumn or early winter it is better to use the model run with no ice.

The model predicts the expected sidewalk status taking into account the past (initialization phase) and the forecasted weather. The model calculates a slipperiness index and classifies the level of slipperiness on the sidewalks into three classes: normal, slippery and very slippery. During very slippery sidewalk conditions, normal walking is challenging for everyone and extra care must be taken when walking.

The most slippery cases for pedestrians with low friction occur when there is dry, loose snow or a thin water layer on an icy surface. The layer of water on ice may originate directly from rain or from melted ice or snow on and around the sidewalk. Snow on the icy surface can be hazardous, because pedestrians do not necessarily notice the ice below the snow. In certain circumstances, foot-packed (compressed) snow as well as freezing conditions can result in a very slippery surface.

Slipperiness categorization in the RoadSurf-Pedestrian has six different indices and three different warning classes:

1. No slipperiness → normal sidewalk condition
2. Slippery → typical normal winter weather when slipperiness may occur here and there
3. Foot-packed snow → very slippery and warning is suggested by the model
4. Freezing → very slippery and warning is suggested by the model
5. Snow above ice layer → very slippery and warning is suggested by the model
6. Water above ice layer → very slippery and warning is suggested by the model
The slipperiness index and slipperiness classification have been developed using slipping injury data gathered from different sources. Weather conditions especially on peak days of the slipping injuries have been analysed in detail and the reasons for the slipperiness have been examined. There have also been several measurement campaigns in cooperation with the Finnish Institute of Occupational Health, and their slipmeter observations have been used in the model development (Ruotsalainen et al., 2004). Then, using all the collected slip injury data, slip measurement and weather observation data, an empirical deduction chain leading from weather parameters, surface condition and surface temperature to slipperiness index has been developed for the model. The deduction chain is based strongly on storages, precipitation and temperature values. Previous weather up to 3–4 days back often has a strong impact on prevailing and upcoming slipperiness, and has been accounted for in the model. Non-meteorological factors, such as sidewalk maintenance practices and local small scale conditions, are not included in the model and may induce incorrect results. The RoadSurf-Pedestrian expects open areas and it does not take into account, for example, surrounding trees or buildings obscuring radiation, which can play a crucial role affecting the surface temperature especially within urban areas. The volume of pedestrians causing wearing and interacting with the storages is assumed to be constant everywhere. The model warns about slipperiness if it is predicted to occur generally and widely. Slipperiness may occur locally (e.g. frozen puddles) also when the model does not give information about slipperiness.

The numerical model is a tool for meteorologists when determining the need for warnings about slippery sidewalk conditions during wintertime. RoadSurf-Pedestrian is running operationally once an hour alternating between two different initialization states (ice and no ice). For the meteorologists, colour coded maps of the pedestrian index are provided (Figure 7). Furthermore, meteograms including different weather parameters and pedestrian index are available for 27 pre-defined locations around Finland. Meteograms also include a 4 day history to help the meteorologist get a better picture of the weather development leading to the prevailing and upcoming slipperiness.

3.3 | FMI weather warnings

The FMI's Weather and Safety Centre produces weather services important to public safety. The operational Weather and Safety Centre is run 24/7/365. Its key services are to provide nationwide 10 day weather forecasts as well as weather or weather related warnings up to 5 days ahead. The warnings are routinely updated every 3 hr and, if necessary, updated also at other times.

Figure 8 gives an example of a weather warning map provided by the FMI. Up-to-date warning maps are

![An example of the pedestrian slipperiness index produced by RoadSurf-Pedestrian, visualized by the Grid Analysis and Display System](image-url)
available online on the FMI’s internet site and on the FMI’s weather application on mobile phones. Yle, the Finnish Broadcasting Company, presents the warnings issued by the FMI in their weather forecasts on TV and radio. Warnings are issued, for example, when heavy rain, strong wind, cold or heat waves, or hazardous driving or slippery sidewalk conditions are to be expected. Warnings are issued to targeted regions (sea areas, regions or municipalities in Lapland); nowadays, also freely defined areas determined by duty meteorologists can be used. The severity of the awareness level is shown by a colour-coded map to represent four levels of warning: red to indicate exceptional risk from hazardous weather conditions, down through orange and yellow to green, indicating that severe weather is not expected. The level of awareness is the same as that provided by the European Meteorological Network at the MeteoAlarm website (www.meteoalarm.eu/) which gives information on potential meteorological risk and awareness over the European geographical domain.

One of the FMI warnings is the slipperiness level on pedestrian sidewalks. Meteorologists decide about warnings by combining available weather observations and forecasts and using their own expert judgement and knowhow. The warning specifies the cause and duration of slippery conditions. During the winter, there are typically 5–20 days per region when slippery sidewalk warnings are issued. In these circumstances, extra care should be exercised when walking by carefully choosing footwear and using slip guards, if possible. In addition to the FMI’s warning map, slipperiness warnings can be delivered via SMS or different online services. For example, cities and companies can also purchase tailored services and inform their citizens or employees about slippery sidewalk conditions (Hippi et al., 2017).

One criterion for issuing warnings is that slipperiness should occur generally and widely in the region. In practice, it is not possible to issue warnings with very high spatial resolution, and locally slipperiness may thus occur also when no warning has been issued. In the beginning of the winter season, the threshold for issuing the warnings is kept somewhat lower, because people tend to have difficulties in adapting even to milder slippery conditions after the summer season.

4 | MODEL VERIFICATION EXAMPLES

For verification purposes, the slipperiness index produced by the RoadSurf-Pedestrian model and the warnings issued were compared to slip injury statistics which were collected from commuting accidents by the TVK. Section 4.1 presents the reported daily number of slipping injuries compared to the modelled pedestrian index and warnings as well as to some modelled and observed weather parameters for winter 2011–2012 in the Uusimaa region. Section 4.2 presents a case study with a model run for one very hazardous day for pedestrians, February 20, 2017, with a high amount of slipping injuries based on TVK’s slip injury data.

4.1 | Winter season 2011–2012

The RoadSurf-Pedestrian model was run for the winter season 2011–2012 from November to April for the Uusimaa region. Winter 2011–2012 was chosen for the verification case because it was very challenging due to the high amount of snow, and the Uusimaa region covers about 30% of the Finnish population. Meteorological observations were used as input data, so the uncertainty of the forecast data was eliminated from the results. Observations were obtained from a 10 km × 10 km grid, and the closest grid point was selected to obtain the data. Solar radiation measurements were not available and they were obtained from a numerical weather prediction model, using data from the closest grid point in the operational grid. The injury statistics were from the Uusimaa
region but weather observations were from Helsinki Kumpula weather station and modelled data were the closest point from Helsinki, Kumpula.

Figure 9 presents the results for the verification with weather observations, modelled data, issued warnings about very slippery sidewalks and slipping injury statistics. The figure consists of four panels (a)–(d). Panel (a) presents modelled hourly road surface temperature ($T_{surf}$), observed daily maximum temperature ($T_{max}$) and observed daily minimum temperature ($T_{min}$). Panel (b) presents daily snow cover measured daily at 6000 UTC and daily precipitation amount. Panel (c) shows modelled pedestrian index value (1–6; see the definitions of the values in Section 3.2) as red columns (PedIdx) and issued warnings as blue markers (Warning). Finally, panel (d) shows the daily numbers of slipping and falling injuries from the Uusimaa region. TVK's injury data were corrected as in Section 2.3. The red horizontal line shows the peak day limit for slipping injuries (36). It was defined using a Poisson distribution when the number of injuries exceeds the number with probability 0.01.

The beginning of the winter season in November and December was quite mild; temperature dropped only occasionally below 0°C. However, there are quite a few false alarms of hazardous slipperiness during November and December when the pedestrian index (PedIdx) gets values of 3, 4, 5 or 6 but the slipping injury columns are relatively low. The snowy season started at the beginning of January when the first high columns can be seen in the slipping injury data; also the model indicates slipperiness and a couple of warnings have been issued. In the middle of January it was snowing for many days and the snow cover quickly reached 40 cm. Lots of injuries occurred during those days with snowfall; also the model gives slippery conditions and several warnings were issued by the duty forecaster. From the end of January until the middle of February, when there was a real winter season with temperature continuously below 0°C, slipperiness did not occur and the number of injuries was quite low. After that, in the second half of February, there were a couple of very snowy days; warnings were issued and suggested by the model. Starting from the end of February, the temperature was around 0°C and slippery conditions existed every now and then. In March the temperature varied around 0°C and snow melted quite fast, and also short wave radiation became effective causing a large variation in the road surface temperature. At the beginning of April there was a short snowy season and a peak is also evident in the injury data, but no warnings were issued although the model gives information about slipperiness.

The number of peak days (daily injuries $\geq 36$) was 24 in total, which is a rather high number, most probably due to the very snowy winter season. As can be seen from Figure 9, the model overestimates slipperiness; on the other hand, there are also days with lots of slipping injuries with no indication of slipperiness predicted by the model. In contrast, the number of issued warnings (13) is lower than the number of peak days and the issued warnings are not always the same as the detected peak days of slipping injuries. This illustrates the challenge of

![Figure 9](image.png)

**Figure 9** Model verification case for Helsinki/Uusimaa for winter 2011–2012. Weather observations ($T_{maximum}$, $T_{minimum}$, snow cover and daily precipitation), modelled data ($T_{surface}$, PedIdx is the pedestrian index), issued warnings and daily pedestrian slipping injuries based on the Finnish Workers' Compensation Center data. More detailed information about panels (a)–(d) can be found in the text.
modelling and predicting slipperiness. Duty forecasters should find a balance when giving warnings. Warnings should be issued always when hazardous sidewalk conditions are expected, but too many warnings when slipperiness does not occur can decrease the value of the information.

Table 3 presents the hits and false alarms for the winter 2011–2012 data. The daily slipping injury data were divided into three categories using a Poisson distribution:

- Peak days of slipping injuries, when the number of daily slips is equal to or greater than 36 ($p < .01$).
- Potential peak days of slipping injuries, when the number of daily slips is equal to or greater than 28 but less than 36 ($0.1 < p \leq .01$).
- Days that are not peak days or the potential of peak days of slipping injuries ($p \geq .1$).

Slipping injury categories were compared to issued warning data (on/off) and modelled pedestrian index data (warning suggested on/off). In this study a warning was suggested by the model if a PedIdx value of 3–6 exists for 6 hr or more per day. The results show that the modelled data correlate better with the peak days of slipping injuries than with issued warnings. On the other hand, the modelled data give more false alarms on non-slippery days than warnings that were issued.

One must bear in mind that the RoadSurf model has not been developed for this kind of long run for one point so the results are more or less indicative. The parameter development (especially storages) during the long run may be problematic and is not working quite properly. Also, weather observations and modelled data are in this case from Helsinki which is not always a good assumption because the slipping statistics cover the whole Uusimaa region. Furthermore, a point forecast, although being a reasonable approximation of the region, gives limited information about the situation in the whole area.

4.2 Case study February 20, 2017

According to TVK’s data February 20, 2017, was the most slippery and hazardous day for pedestrians during 2017, especially in the southern and western parts of Finland. A total of 921 pedestrian slipping injuries occurred on that day for the whole of Finland (485 in the Uusimaa region), whereas the average daily value for slipping injuries for the winter months from November 2016 to April 2017 in the whole of Finland was 66.9 (28.3 in the Uusimaa region). Nine hundred and twenty-one pedestrian slipping injuries per day is a very high number, the highest number per day typically being between 200 and 450 per winter except for November 24, 2008, when the number of slipping injuries was slightly over 1,000.

Figure 10 presents the weather development during February 18–20, 2017. On the first few days, February 18–19, 2017, the weather was quite mild in the southern and western parts of Finland, air temperature was between 0°C and 5°C, there was a small amount of precipitation in different forms in many places, and snow cover was 0–10 cm. In the eastern and northern parts of Finland the temperature was lower and there was more snow on the ground. On February 20 the temperature started to drop due to a cold front pass and surfaces froze. Also, there was light snowfall on February 20 so surfaces turned very slippery, not only due to freezing but also because of snowfall.

RoadSurf-Pedestrian was run the way it is used operationally. There was a 96 hr long initialization phase and after that a 48 hr long forecast part. The visualization reproduces the slipperiness forecast the way the duty forecaster would have seen it on the previous evening.

### Table 3 Verification for the different peak day definitions (peak day, potential peak day and not a peak day or potential peak day), issued warnings and the warning suggestion by RoadSurf-Pedestrian for the winter season 2011–2012

|                      | Warning on $N = 13$ | Warning off $N = 169$ | Warning suggested by the model $N = 35$ | Warning not suggested by the model $N = 147$ |
|----------------------|---------------------|----------------------|----------------------------------------|---------------------------------------------|
| Peak day             | 5                   | 19                   | 10                                     | 14                                          |
| (injuries $\geq 36$  |                     |                      |                                        |                                             |
| $N = 24$             |                     |                      |                                        |                                             |
| Potential peak day   | 0                   | 13                   | 3                                      | 10                                          |
| ($28 \leq$ injuries $< 36$) |           |                      |                                        |                                             |
| $N = 13$             |                     |                      |                                        |                                             |
| Not a peak day or    | 8                   | 137                  | 22                                     | 123                                         |
| potential peak day   |                      |                      |                                        |                                             |
| (injuries $< 28$)    |                     |                      |                                        |                                             |
| $N = 145$            |                     |                      |                                        |                                             |
The pedestrian index calculated by RoadSurf-Pedestrian for the case starting from the 19 February evening with 2 hr intervals is presented in Figure 11. Different values of the pedestrian index can be seen, revealing that the weather was changing from a melting situation (water on ice and temperature above...
0°C) (red) to freezing temperatures (orange) and light snowfall (violet) with foot-packed snow (blue). On that day a warning was issued to the southern regions of Finland.

5 | DISCUSSION

An operative system to observe the slipperiness on pedestrian sidewalks is lacking, so far. On the Finnish road network, the road weather observation network is quite dense. However, road weather conditions and pedestrian sidewalk conditions are not always the same and there is a need for specific slipperiness observations for sidewalks. Furthermore, severe road weather conditions and slippery sidewalk conditions often occur on different days (Ruuhela et al., 2005). Because of this, road weather observations cannot directly be used to replace pedestrian sidewalk observations. Car traffic typically has problems and there are a lot of accidents in the case of snow due to reduced friction and visibility (Juga et al., 2010). New snow is not necessarily slippery from the pedestrians’ point of view. However, if the surface were already icy, even a light snowfall might be hazardous for pedestrians (Penttinen et al., 1998; Anttila, 2001). Also, in certain weather and pedestrian volume conditions new snow may be packed into a slippery layer.

The level of slipperiness on the sidewalks can be detected also by foot and eye. Recent developments in citizen science provide new possibilities to increase the number of observations. The FMI has developed a weather application (FMI Weather app) that is available for mobile phones (Android and iOS) (Karjalainen and Jokinen, 2019). The application includes a tool to report citizen observations (My observations), with slipperiness from a pedestrian’s point of view being one of them. Citizen observations are a valuable new source for getting more observations of different weather or weather related phenomena. This has a real impact on the weather forecaster’s decision-making when making weather forecasts and issuing weather warnings (Karjalainen and Jokinen, 2019). However, citizen observations need strict quality control procedures to filter out unreliable measurements (Nipen et al., 2019). Another new innovation to determine the risk of slippery sidewalks is the accelerometer on smartphones which can estimate slipperiness based on walking acceleration (Saida et al., 2019). When widely used, it could also provide reliable information on local slipperiness. Real time observations about prevailing slipperiness could give valuable input to improve model development and help decision-making when duty forecasters are issuing warnings about slippery sidewalk conditions.

Elderly people and people with decreased locomotion balance are more fragile for injuries than younger people. Slipping injuries are expected to become more common in Finland in the future as the population is ageing (Statistics Finland, 2018). In contrast to the young, older people have a higher risk of fractures as a result of falls, with slow healing and a high risk of serious consequences (Mänty et al., 2006). In the older age groups, falls and slips are clearly more common for women than for men (HaikonEN et al., 2010). The use of anti-slip devices has become more common, especially among some professional groups (e.g. in mail delivery and in rail yard work) and among the elderly and joggers (Juntunen et al., 2005; Vartiainen et al., 2009). In Finland, several cities provide free shoe grips or shoe studdings for elderly residents. It has been said that “Even one fall fewer and this project has paid for itself” if elderly people are kept out of hospitals and helped to avoid fractures (BBC, 2016). This is a good example of an injury protection campaign provided by society.

As a result of global warming the climate will change, and wintertime temperatures are predicted to rise leading to a situation where freezing-point days will become more frequent throughout the whole country (Jylhä et al., 2009). However, in the longer run the winter season in the southern part of Finland is expected to become shorter, which may decrease the number of slip injuries (Saranko, 2019). The importance of the topic will become more important in the future, because walking and cycling are increasing rapidly in several urban areas. There could be collaboration between different countries to exchange methods and results.

6 | CONCLUSIONS

The weather service for pedestrians in Finland is a good example of a service that has been developed for a need identified by decision-makers. Wintertime slipping injuries are common and lead to substantial economic costs to health care and losses to the society due to long sick leaves. In this paper, the service and related slipperiness warnings as well as the RoadSurf-Pedestrian model in its current state, after a gradual development over a period of two decades, have been described. During the development phase, there have been several challenges that still limit the accuracy of the operational modelling and forecasting of pedestrians’ sidewalk conditions: lack of slipperiness observations, different rules and practices of sidewalk winter maintenance, and the varying number of pedestrians in different areas. All these can cause big differences in local slipperiness within short distances and make the estimation of slipperiness difficult. As the
verifications reveal, there are still some challenges in the modelling of slipperiness but the model already gives new valuable information on slipperiness for the duty forecasters. More complete verification should be done to get information on the limitations and bottlenecks of the model. Verification results would also be beneficial for further model development.

There exists considerable potential to reduce the level of slipping risk and thus decrease economic losses and human suffering. Better awareness of slippery sidewalk conditions can be expected to impact the safety of winter-time walking. Reliable weather and sidewalk condition forecasts can improve pedestrians’ road safety by reducing the risk of accidents in several ways. People can choose proper footwear or use of anti-slip devices, choose the route, change the mode of transport, postpone the journey or cancel it altogether. Also, precise and reliable weather and sidewalk condition forecasts enable targeted and more effective sidewalk maintenance activities to improve the grip of sidewalks as well as to reduce the risk of accidents and injuries (Hautala and Leviäkangas, 2007).

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