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Injury Reducing Effect of GSHP-Heated Pedestrian Paths

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ABSTRACT

In Sweden, falls amongst pedestrians during wintertime, due to slipping on ice and snow, is a costly and growing problem. Using data on pedestrian falls from four Swedish cities, the injury-reducing effect of heated surfaces was studied. The results indicate that heated surfaces have a significant injury-reducing effect especially in cities with more ice and snow. Currently, district heating is used as a heat source and at an increasing cost. By using GSHP systems as a heat source, the cost could be considerably lowered, and in this way secure the further use and expansion of heated pedestrian paths.

INTRODUCTION

Since 1997, traffic safety measures in Sweden have been based on what is commonly called the Vision Zero Statute, which has successfully contributed to reducing the number of deaths in vehicles (Swedish government, 1997; Johansson, 2009; Belin et al., 2012). However, although the strategy may have contributed to a reduction in the number of fatalities among motor vehicle accidents (Belin et al., 2012; IRTAD, 2019; Tingvall & Haworth, 1999), the same development is not observed when considering *Vulnerable Road Users* (VRU), such as pedestrians, cyclists, or moped/MC riders (IRTAD, 2019; Värnild et al., 2019; Weijermars et al., 2018; WHO, 2018).

Pedestrian single accidents, in other words *Pedestrian Fall Injuries* (PFI), are not (yet) included in the international definition of road accidents as no vehicle is involved (Berg et al., 2016; Methorst et al., 2017; Amin et al., 2022). However, PFIs account for a large proportion of injuries and deaths that occur in the road traffic environment (Aldman et al., 1976; Schepers, 2017; Aldred, 2018; Elvik & Bjørnskau, 2019; Amin et al., 2022). In Sweden, at least 12,000 PFIs occur annually, and half of these injuries result in permanent medical impairment; 2.2 times more compared to car occupants (Amin et al., 2022). Sweden, as the first country in the world, has a national target to reduce serious PFIs by 25% between 2020 and 2030 (Swedish Government, 2023).

The majority of PFIs are caused by poor or inadequate maintenance of pedestrian pathways, resulting in slips (due to ice/snow) and trips (due to uneven surface), of which most (85%) occur in urban areas (Amin et al., 2022). In Sweden, icy and snowy conditions dominate as the causal factor, being responsible for almost 60% of all PFIs. To combat these types of incidents, there are various measures available. The most common strategy is to take mechanical snow removal (with ploughs and/or rotary brushes) and/or apply salt and/or sand to ground surfaces. An alternative method, that is increasingly being taken, is to use hydronic heating of streets and pavements, mainly through *Hydronic Heated Pavements* (HHP) systems.

Due to the substantial societal costs of PFIs (the short-term costs (≤6 months after the accident) per average injured individual is estimated to be SEK 54,330 according to the 2014 price level (IHE, 2016:5) which is equivalent to SEK 70,902 ($ 7,900) according to the 2023 price level) it is economically beneficial to remove snow and ice from streets and pavements (Arvidsson & Öberg, 2012). However, the cost-benefit calculations for heated pavements are unknown or even if such interventions are effective, despite heated pavements having been installed in many cities in northern colder climates.

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More importantly, evaluating these types of societal interventions is inherently difficult (Bonander, 2016). Therefore, this paper should be viewed as a starting point, focusing on two specific aims. First, we analyse the injury-reducing effect of heated ground surfaces to reduce PFIs in four large Swedish cities that were chosen to represent the different geographical areas. Secondly, we wanted to compare the cost and efficiency of using three different energy sources for ground heating: 1) district heating return, 2) electric cables, and 3) *Geothermal Heat Pumps* (GHP). In addition, our study will determine whether heating of ground surfaces a plausible safety intervention and which technology is the most efficient and cost effective.

MATERIALS AND METHODS

Heated pavements

Currently 22 cities in Sweden operate HHP systems, which represents a total ground surface area of approximately 600,000 m^2. These HHP systems were mainly installed in busy urban areas along pedestrian walkways, and for the most part is connected to district heating systems. However, many of these systems are encountering steadily increasing costs of operation and suggestions have been made to use GSHP systems to reduce these costs (Andersson et al., 2023).

Conventional HHP system design

In the northern European counties, the most common strategy for dealing with icy ground conditions is the use of friction melting by spreading (i) a freezing point depressant such as sodium chloride (salt) and/or (ii) an abrasive material such as sand (Minsk, 1998). An alternative method is to use thermal energy by means of a HHP system within or underneath the pavement for melting ice and snow.

Generally, a HHP system consists of three major components: the pavement, a source of thermal energy, and control system to regulate the temperature. It is also possible to additional devices to remotely observe ground surface conditions, such installing a local weather station and a camera system to visually monitor the pedestrian pathway. Usually, the HHP system is constructed with a top layer of asphalt/concrete that covers a horizontal network of plastic pipes, that typically are at a depth of 60–100 mm and are spaced 200 mm apart. Under the horizontal pipes, a layer of insulation is installed to reduce heat loss to the ground. The pipes are made of coupled or fused polyethylene (PEX) having a diameter of 20–25 mm. The pipes are laid out in parallel loops, which are commonly 200 m or less in length. In some installations the ground surface temperature is monitored with thermocouples embedded into the pavement. The monitoring system allows the amount of energy applied to be controlled and optimized. Being integrated with weather forecasting provides the possibility of preheating the ground surface before ice and snow accumulate. Alos, the weather forecasting system should be able to predict ice formation on the pavement (for de-icing) and predict snow precipitation (during snow melting).

The actual heating demand of HHP systems varies with the climatic conditions and the type of pavement used. It is also affected by the intensity of snowfall; under most scenarios the falling snow should be melted before accumulating. The operational strategy used also is a major factor to the HHP operation. Usually, the pavement is preheated at low power and when the temperature decreases rear zero, when frost forms, but when the snow begins to fall the amount of heating applied increases significantly. The amount of thermal energy required for keeping the pavement above freezing also affected by wind speed and direction, as well as several other parameters (Person, 2007). As such, the issue of dimensioning is extremely complex and difficult to predict. For this reason, it seems that most existing HHP systems are empirically dimensioned to operate with 250–350 W/m^2, which run at its maximum can attain a supply temperature of 35°C (Andersson et al 2023). Whilst there are few studies that have analysed how effective a HHP system is as a solar collector, a case study performed at Stockholm Arlanda airport indicates that temperatures of up to 30–35°C can be achieved from a HHP system on a gate with concrete (Persson, 2007).

Alternatives with geothermal systems

Sweden has a long tradition in using shallow geothermal systems, especially smaller GSHP applications with vertical or horizontal loops (closed loop systems), but also systems that use groundwater as a heat source (open loop systems). Another group of commercial systems are *Underground Thermal Energy Storage* (UTES) systems that are used for both heating and cooling. The two most common UTES systems are *Aquifer Thermal Energy Storage* (ATES) and *Borehole Thermal Energy Storage* (BTES). There are thousands of these in operation all over Sweden of which only a few for HHP applications (Gehlin et al 2022; Andersson et al 2023). An advantage of using ATES and BTES for HHP applications is that they are capable to collect and store solar energy that are obtained from the HHP pavement during summer. For this reason, they are the most promising geothermal alternatives, principally illustrated in Figure 1.

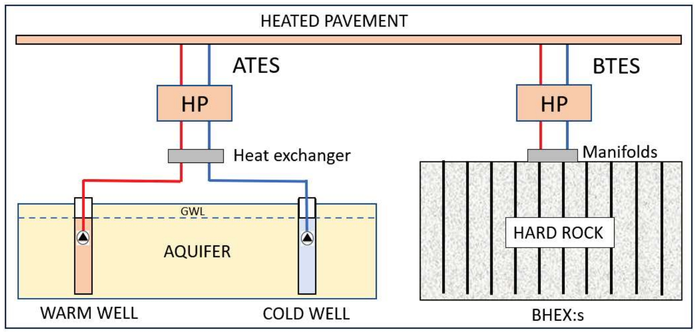

Figure 1. The principle of GSHP systems with seasonal storage applied for HHP system in Sweden.

Conventionally designed, ATES is divided into a warm and a cold aquifer side with all wells equipped with submersible pumps making it possible to reverse the flow direction. In summer, groundwater is pumped from the cold wells and injected into the warm ones. In winter, the flow direction is reversed. Warm water is pumped to the HHP system, and the chilled water is injected through the cold wells. The advantage of using ATES is that the temperature stored in summer can be directly used in the winter. The most prominent drawback is that suitable aquifers are rare to find close to city centres (Andersson et al., 2023).

BTES systems consist of many vertical boreholes drilled into hard rock. The boreholes are commonly 200–300 m deep, completed with single U-pipe, referred to as a *Borehole Heat EXchanger* (BHEX). The boreholes are connected in parallel by an underground horizontal pipe system. The most prominent advantage of using BTES is that it can be applied in almost any geological condition. Moreover, boreholes can be drilled in most urban environments. The main drawback is the poor thermal efficiency of the BHEX, that will limit the direct use of BTES temperature (Andersson et al., 2023).

There is limited data on the energy demand for HHP systems. However, studies indicate an annual consumption of 250–400 kWh/m^2, or 325 kWh/m^2 as a mean value (Andersson et al., 2023). The mean cost for heat supplied by district heating in Sweden in 2023 is about SEK 900 ($ 90)/MWh (Nils Holgerson-Gruppen, 2023) meaning that the mean annual energy cost for district heated pavements is SEK 290 ($ 29)/m^2. Based on the spot price, the transmission fee, and governmental taxes, the average price for electricity in Sweden was SEK 1,300 ($ 130)/MWh in 2023. Using these costs for 1,000 m^2 heated pavement, with an annual energy demand of 325 MWh, the energy cost for using ATES and BTES systems have been calculated (Table 1). In this case the *Seasonal Performance Factor* (SPF), is defined as the output of thermal energy over the input of electricity to run the system for a full year (SPFH1 according to Gehlin and Spitler (2022). The estimations are based on experiences from larger space heating projects using the same GSHP technologies. As indicated in the table, the saving potential using ATES or BTES is in the order of 70–85% compared to systems using district heating (Andersson et al., 2023).

Table 1. Energy costs of different systems for 1,000m^2 heated pavement

Heating System	**SPF**	**Electricity use** [MWh]	**Annual energy cost** [SEK]/1,000 m^2
District heat	1	0	290,000
ATES	10	33	43,000
BTES	5	65	85,000

Note: (SEK 10=$1 USD)

PFI accident data and analysis

In terms of the effect of heated pavements on PFIs, four cities were purposefully chosen to represent a large regional (or national) centre representing the southern part of the country (Helsingborg), the western part of Sweden (Gothenburg), eastern areas (Stockholm), and the far north (Umeå). In terms of data collection and availability, two sources were used: i) the location of heated streets and pavements in the cities, and ii) the PFIs of the four cities. Data on PFIs was obtained through the *Swedish Traffic Accident Data Acquisition* (STRADA), a national information system containing data on all traffic-related injuries of the Swedish road transport system. For a more comprehensive description of STRADA, see Howard & Linder (2014). Records containing the geographic location of all PFIs, as well as all other information regarding the accident and injury that occurred between 2007 and 2014 were extracted and plotted on a map. The data were then categorised by season and accident type, and then normalised with respect to the summer period (assigned a value of 1).

To determine exactly the effect of the heated surfaces it would have been desirable to have an exposure measurement, to assess whether there were differences in the number or proportion of individuals that travelled on heated and unheated ground surfaces. Because this data was not available, the induced exposure method was used instead. The method has been proposed as a case-control method to estimate relative risk in the absence of exposure data (cf. Carr, 1969; Haight, 1973; Stamatiadis & Deacon, 1997). In this study, the measure is equal to the number of pedestrians injured in winter due to reasons other than slipping on ice or snow. Furthermore, the PFIs on unheated surfaces (controls) in winter are directly proportional to their exposure. We assume that the cause of the other injuries is not due to slipping on ice and snow, according to the STRADA categorisation. As such, for each city an *Odds Ratios* (OR) analysis was performed (Table 2).

Table 2. Odds ratios of natural and HPP ground conditions.

	Falls/slip due to ice/snow	All else	Total
Unheated pavements	a	b	a+b
Heated pavements	c	d	c+d
Total	**a+c**	**b+d**	**a+b+c+d**

For the OR, a *Standard Error* (SE) and 95% *Confidence Interval* (CI) are calculated according to (Altman, 1991):

$$\text{OR}=(a/b)/(c/d)=(a*d)/(b*c) \quad (1)$$

$$\text{SE}\{\ln(\text{OR})\}=\sqrt{(1/a)+(1/b)+(1/c)+(1/d)} \quad (2)$$

$$95\%\ \text{CI}=\exp(\ln(\text{OR})-1.96\times\text{SE}\{\ln(\text{OR})\})\ \text{to}\ \exp(\ln(\text{OR})+1.96\times\text{SE}\{\ln(\text{OR})\}) \quad (3)$$

Where zeros cause problems with computation of the odds ratio or its standard error, 0.5 is added to all cells (*a, b, c, d*) (Pagano & Gauvreau, 2000; Deeks & Higgins, 2010). In the present study, the constant 0.5 was added for the data in the city of Helsingborg.

Cost-benefit analysis

To estimate the cost-benefit potential of the different systems, a crude cost-benefit analysis was performed. Put simply – and returning to Table 2 – the relation between *b* and *a* was deemed as the norm. Therefore, a hypothetical "non-effected" *c* was calculated from the perspective of scaling *d* in the same proportion as *b*:*a*. This then produced a contrafactual number of increased injuries that would have occurred had no heated pavements existed during the entire study period. This number was then multiplied by the previously mentioned personal injury cost of SEK 70,902 ($ 7,900) and divided by the number of years in the study period. In terms of the costs for the systems, three alternatives were calculated; district heat, ATES and BTES based on the costs in Table 1, along with the total square meters of heated pavements for all the cities combined, taken from Andersson et al. (2023). No comparison between the cities was possible as the available energy cost data was based on Swedish averages. A system in a northerly city such as Umeå would use considerably more than a southerly city such as Helsingborg, and the costs would differ.

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RESULTS

Analysis of injury reduction effect of heated surfaces

Starting with the absolute number of injuries in each city (Table 3), whilst non-ice and snow related injuries seem to occur throughout the year and at roughly the same level regardless of season, ice and snow related PFIs occur during the colder seasons. As is also clear, in the more southern parts of Sweden (Helsingborg and Gothenburg) the prevalence (and proportion) of PFIs related to snow and ice is considerably lower, simply due to fewer days with snow and ice.

The proportion of PFIs due to ice and snow is much less on the heated surfaces compared to the unheated surfaces (Figure 2). During the winter period, the proportion of PFIs related to ice/snow on heated surfaces compared to unheated surfaces was 100% less in Helsingborg, 63% less in Gothenburg, 61% less in Stockholm and 79% less in Umeå (when autumn and spring were included these numbers increased to 67% for Gothenburg, 68% in Stockholm, and 83% in Umeå).

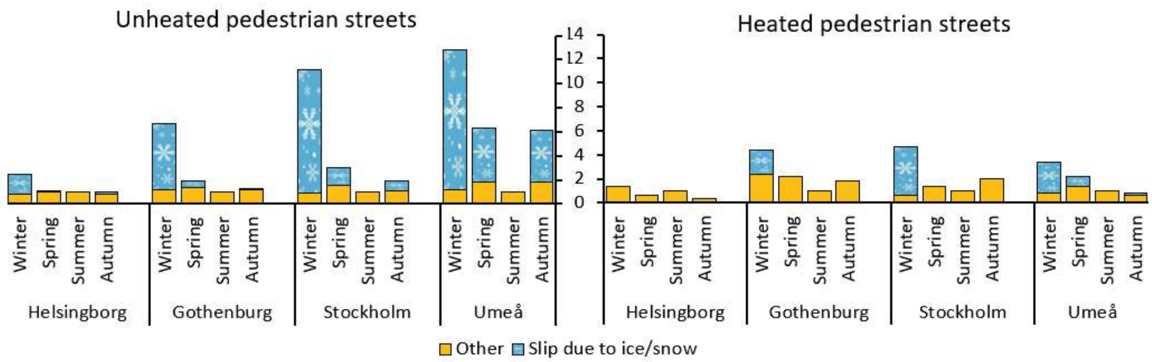

Figure 2. Distribution of fall-related accidents among pedestrians over the years 2007-2014 (Summer normalised to value 1)

Likewise, in terms of OR for not being injured, the lowest OR was found for Stockholm, with a non-significant value of 2.35 while the ORs for Gothenburg, Helsingborg, and Umeå were statistically significant, showing an increased odd of 4.28, 19.80 and 3.53 respectively. In addition, according to the induced exposure method, pedestrians i.e. in Gothenburg, walked four times more on the unheated surfaces, but were injured due to ice or snow 23 times more (N.b. this assumes that all other factors remain the same) (Table 3). When a total OR for all four cities was calculated, a statistically significant OR of 3.78 was shown.

Table 3. Occurrences and Odds Ratios of Pedestrian Fall Injuries on unheated and heated pavements.

City	Type of pavement	Slip due to ice/snow	All other	Total	OR	95% CI	z-statistic (*p*-value)
Helsingborg	Unheated	38	17	55			
	Heated	0	4	4			
	Total	**38**	**21**	**59**	**19.80**	**1.01–388.24**	**1.966 (0.0493)**
Gothenburg	Unheated	230	49	279			
	Heated	34	31	65			
	Total	**264**	**80**	**344**	**4.28**	**2.41–7.62**	**4.945 (0.0001)**
Stockholm	Unheated	516	44	560			
	Heated	30	6	36			
	Total	**546**	**50**	**596**	**2.35**	**0.93–5.94**	**1.799 (0.0721)**
Umeå	Unheated	106	10	116			
	Heated	48	16	64			
	Total	**154**	**26**	**180**	**3.53**	**1.49–8.35**	**2.875 (0.0040)**
All 4 cities	Unheated	890	120	1010			
	Heated	112	57	169			
	Total	**1002**	**177**	**1179**	**3.78**	**2.60–5.47**	**7.008 (0.0001)**

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As is seen in Table 4, based on a Swedish average, an estimated 1,313 injuries were prevented between 2007–2014 in the four studied cities, resulting in an average of 164 injuries per year. The estimation has been made according to Table 2 by "(a/b)*(b+d)" and with the assumption that 'other injuries' are unrelated to whether the pavement is heated or not. In terms of a crude cost-benefit analysis, only the ATES system would be cost effective whilst the BTES system would give a 51% return and the district heat a 15% return.

Table 4. General cost-benefit analysis of different the HHP systems

City	Estimated number of prevented injuries	Costs per PFI [in 1,000 SEK]	Heated surface [1,000 m^2]	Energy cost [in 1,000 SEK] District heating	ATES	BTES
All 4 cities	164	71	162	290	43	85
Total cost		11,644		46,980	**6,966**	13,770

Note:(SEK 10=$1 USD)

DISCUSSION

This study clearly draws several important conclusions about heated pavements and PFIs. First, the results show that heated pavements are an effective intervention for reducing PFIs that are from slipping by ice and snow. In terms of the odds of preventing an injury, the greatest impacts were found in the two southern most cities (Helsingborg and Gothenburg), while in terms of absolute numbers, the two northern most cities (Stockholm and Umeå) HPP systems had the greatest PFI reductions. While somewhat surprising in terms of OR, it is worth noting the very large confidence intervals for Helsingborg and Gothenburg. As such, we would argue that the overall findings and the absolute numbers are perhaps more relevant, and the greatest impact would be in cities with longer periods of snow and ice accumulation. In the comparison between the different types of HPP system, and the cost-benefit, the ATES and BTES geothermal systems are cheaper than tapping thermal energy from district heating systems. Only the ATES scenario was shown to be cost effective. However, it is important to note that ATES systems cannot be installed in all locations and that the first cost of BTES and ATES systems is higher. Despite the higher installation costs, the difference in costs over the period of operation is considerable.

The effectiveness of heated paths on snow and ice related PFIs is especially interesting given the lack of PFI-reducing interventions currently available. Evidence-based injury-reducing strategies have been introduced, such as studded footwear (Berggård & Johansson, 2010), but these strategies have primarily focused on shifting responsibility to the individual rather than ensuring that society creates safe, secure, and attractive environments for pedestrians, i.e., the opposite of the foundations of the Vision Zero approach (Tingvall & Haworth, 1999). Heated paths are therefore clearly in line with the current modus operandi of traffic safety. Also, heated paths could have further benefits. The effect of snow and ice on physical activity is considerable (Cepeda et al., 2018) and it can be presumed that efficient removal of ice and snow will encourage walking as a mode of transport. As it is estimated that a quarter of the global population is insufficiently active due to a lack of physical activity such as walking (WHO, 2015), the importance cannot be overstated. Despite not including these types of benefits that could arise by using heated paths – as well as potential gains in terms of reduced emissions and reduced noise pollution from not requiring snow clearing machinery, the value of automation and the reduced need for sand and salt – the crude cost-benefit analyses in this study still shows favourable results for the GSHP system ATES. However, from a Swedish perspective the fact that the current choice – district heat – is not the most cost effective is somewhat problematic. Also, previous research has indicated that CO_2 emissions from the three different systems vary greatly with district heat emitting 16,250 kg per 1,000 m^2, while the equivalent figures for the GSHP systems BTES and ATES are 650 kg and 175 kg, respectively (Andersson et al., 2023).

Whilst we do not argue for replacing well-functioning systems, it is important for future societies contemplating an installation of heated path systems to be aware that GSHP systems seem to be considerably more cost effective if the geological conditions and/or positioning of the community allows for such systems. This is despite installation costs for GSHP systems often being higher than district heat solutions. For example, according to Andersson et al. (2023), a BTES system for 1,000 m^2 would require approximately 6,000 m BHEXs, using 20 boreholes, 300 m deep, the additional investment cost would be in the order of 3 million SEK ($ 300,000). However, given the large differences between district heat and the alternative systems, such costs are easily paid off over the lifetime of the systems.

There are some limitations in this study that should be noted. First, we have compared the same cities and the same time interval, but whether pedestrian flows (exposure data) on the different streets chosen for the study differ, or whether the type of pavement differs between the streets, is not known. Second, although the STRADA register offers a unique opportunity to study PFIs using data reported by every emergency hospital in Sweden, there was a limitation in STRADA because the heated surfaces were not highlighted in the accident database. As such, this needed to be done manually, in turn meaning that errors cannot be ruled out. Further potential errors include the fact that some injured individuals may not seek treatment and some events may not have been reported to STRADA because of, for example, shortages in hospital staff. However, it is unlikely that such aspects have more than a minimal effect on the results. Third, the results are specific to Swedish conditions. As such, the results – especially those related to falls due to slippery road conditions – may not be generalisable to countries located in warmer regions. While we expect that the results should be generalisable to countries with a similar road traffic environment and climate, it would be of considerable interest to see how well our results can be reproduced in other countries. Fourthly, in terms of the crude cost-benefit calculations, these should merely be seen as indications. In reality, several factors are more complex than the model suggests. For example, the energy costs are based on a Swedish average rather than for the specific cities included. Also, heated pavements are not entirely reliable under -13°C meaning that injuries that occurred under these temperatures may not have been hindered through heated pavements. Finally, alternative costs, positive side-effects, environmental factors, carbon emissions, etc., have not been included in the analysis. As such, we want to reiterate the crudeness of the analysis.

CONCLUSIONS

This study's most important finding is the clear effect of heated pavements on the risk of PFIs. The study can also show that the cost-effectiveness improves in parallel to the number of snow and ice related PFIs, and that ATES (and to some extent BTES) systems seem more cost-effective compared to traditional district heat systems. Future studies should attempt to quantify the cost-effectiveness more inclusively on a local level, including more costs (for instance initial investments and maintenance costs) and other benefits rather than merely including running costs and injuries. Also, it would be beneficial to assess tipping points in terms of the number of days with snow and ice when such systems are advantageous to a community.

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