Skid Resistance – Important for Bike Safety

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ABSTRACT

About 8,000 cyclists annually seek medical care at Swedish emergency hospitals. Eight out of ten have been injured in single-bicycle accidents. About 30 per cent of these accidents are skid related. Skid resistance is reduced in wintertime by snow and ice and in summer by grit or leaves and debris on wet surfaces. Research into skid resistance for cyclists has been in progress for several years now at the Swedish National Road and Transport Research Institute. For example, various winter maintenance methods and strategies have been evaluated. Friction measurements have been taken on cycleways, using a Portable Friction Tester. The measurements show great variation in skid resistance, due to winter road conditions, and so winter maintenance methods and strategies play an important role in reducing the number of skid-related bicycle accidents. Paving material is also important, and friction may be reduced by design features such as inlet covers, road markings, and red-painted coat in crossings. In addition to improved winter maintenance, promoting the use of studded tyres for winter cycling could be one way of reducing these accidents. Tyre studies on a specially designed test track have shown that studded tyres could produce a braking friction level 2-3 times higher than that of non-studded tyres. Performance also appears to vary between different studded tyres, depending on brand and number of studs.

Keywords: skid resistance, cyclists, friction measurements, winter maintenance, safety, bicycle tyres.

1 INTRODUCTION

1.1 Bicycle accidents related to the loss of skid resistance

About 8,000 cyclists annually seek medical care at Swedish emergency hospitals. Eight out of ten have been injured in single-bicycle accidents [1]. About 30 per cent of these accidents are skid related [2]. Skid resistance is reduced in wintertime by snow and ice and in summer by grit or leaves and debris on wet surfaces (Figure 1).

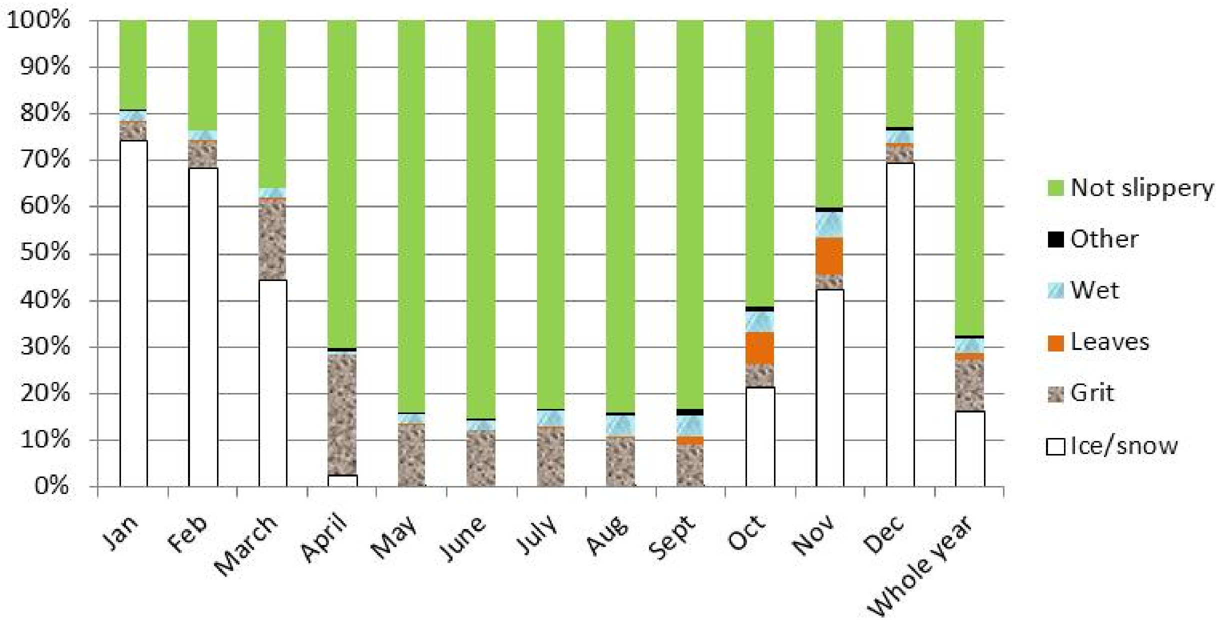

Figure 1. The monthly distribution of single-bicycle accidents in Sweden related to slipperiness, according to data from hospital A&E departments recorded in 2007-2011 (n=19,635) [2].

1.2 Winter cycling in Sweden

Judging solely by the accident statistics, one might conclude that we should not encourage cycling in winter in Sweden. Health and environmental considerations, however, both argue in favour of wintertime cycling. Short car trips are responsible for a relatively large proportion of the emissions caused by traffic, especially in wintertime when cars are subjected to cold starts. In northern countries, coronary disease incidence increases during winter, due not only to climatic factors but probably also to less physical activity [3].

In wintertime cycling in Sweden declines to about a third compared of the figure in spring or autumn [4]. For those frequently cycling during winter, road condition is more important for their choice of travel mode than temperature and precipitation [5]. Cycleways not cleared from snow, followed by slippery surfaces are the road conditions with the most significant bearing on the decision whether or not to go by bike. Cycle flow measurements in winter in the city of Gävle in Sweden also indicated a drop in cycling frequency during slippery conditions [4].

According to focus group studies, cyclists perceive a considerable increase in the accident risk during winter, due mainly to slipperiness and darkness [6]. Certain places where freezing occurs first, such as bridges and tunnels, are considered most dangerous of all. Grit used for de-icing, but causing an impaired grip on bare road surfaces during mild weather conditions, was also mentioned. In addition, the possibility of taking evasive action to avoid obstacles or conflict is impaired, due to slipperiness caused by ice and snow. Due to the perceived increase in accident risk, a few of the participants in the focus groups stated that they chose not to cycle in winter. The winter maintenance service level also made a significant difference to winter cyclists' daily decisions whether or not to cycle. Cycleways not cleared from snow or covered with icy tracks were reasons mentioned for choosing another mode of transport. Wintertime cycling is also perceived as more time consuming and physically demanding than cycling in summertime, in that the impaired grip caused by snow and ice reduces the energy efficiency of cycling, added to which, extra care is needed in wintertime in order to avoid falls and conflicts with other road-users.

1.3 VTI research relating to skid resistance for cyclists

In view of the above – the large number of skid-related accidents and the importance of a high maintenance service level in order to encourage winter cycling – we need to clarify how we can secure cycleway safety, including sufficient skid resistance, even during winter. Research on this subject has been in progress for several years now at the Swedish National Road and Transport Research Institute (VTI.

For example, various winter maintenance methods and strategies have been evaluated. From 1997 to 2002 a PhD-project was carried out which included evaluative studies of a method using a front-mounted power broom for snow clearance and salt for de-icing [7]. Further studies to evaluate methods and strategies using salt for de-icing of cycleways were carried out in the winter of 2013/2014 in the city of Stockholm [8] and will continue in coming winters in both Stockholm and Linköping. In addition, a method using warm wetted sand for skid control on cycleways was evaluated between 2010 and 2012 in Umeå, in the north of Sweden [9]. Warm wetted sand is a method whereby the sanding material is mixed with hot water while spreading, causing the sand to adhere to a cold surface through a process of melting and freezing. In all these studies, friction measurements have been combined with road condition observations as well as interviews with maintenance operators and road users, etc., to evaluate the maintenance methods in question.

In addition, friction and rolling resistance have been studied using different types of bicycle tyres [10]. In an ongoing study, a test track used to study friction of car and truck tyres on ice has been adapted for studying bicycle tyres as well. Combined with the friction measurements of cycleways, these studies will help to improve our knowledge concerning skid resistance for cyclists.

2 METHOD

The cycleway friction observations in the studies mentioned above will be summarised in this paper. In addition, the friction measurements with studded tyres on ice in the test track will be briefly recapitulated.

2.1 Friction measurements using the Portable Friction Tester

When measuring friction on cycleways, we have used a portable, manually operated instrument, namely "the Portable Friction Tester" (PFT). The PFT was developed at VTI in the early 1980s and is used in research when measuring friction on small surfaces, down to 1 metre in length, where larger equipment is not applicable. It was originally designed to measure friction on road markings but has been proved to be a valuable tool for comparing friction measurements on cycleways [11].

The PFT consist of a three-wheeled trolley with the measuring wheel mounted in front of the two support wheels (Figure 2). The rotation of the measuring wheel is set to a fixed slip of 20 per cent and is equipped with a smooth, standardised friction-measuring tyre, defined in American Society for Testing and Materials [12]. The friction between the measuring wheel and the surface of interest is presented as the friction coefficient, which is the frictional force on the measuring wheel divided by the normal load on the wheel. The minimum, maximum and mean friction of the surface measured is directly presented in an instrument display panel, but the measuring data can also be transferred to a PC for further analyses and presentation.

Figure 2. The Portable Friction Tester used to measure friction on cycleways.

2.2 Test track for measuring friction on ice with bicycle tyres

VTI has a unique tyre test facility (TTF, Figure 3) for measuring the friction forces between tyre and ice. In contrast to road surface friction measurements, where the skid resistance of the road is determined with a fixed specific reference tyre, the tyre friction measurements in the TTF use a reference ice surface condition to compare different tyres. In contrast to asphalt pavements, where reference surfaces have been specified within ISO standards, no official reference ice surface exists. Reference ice surface conditions refer in this paper to an ice surface that is as well specified and repeatable as possible. Many years' experience of conducting tyre measurements on ice with the VTI TTF, has made clear that making ice with reproducible properties is anything but straightforward. The ice temperature is of course a major factor, and the TTF has been designed for accurately controlling that temperature to within less than a tenth of a degree Celsius. It is also important to control the air humidity, which is handled by an air dehumidifier. To represent slippery conditions it was decided to use a smooth ice with a temperature of -3°C, and a humidity of around 70%. This, however, is not enough to guarantee reproducible ice friction conditions. The ice is constructed by repeatedly applying a thin layer of water on top of a frozen steel bar to a thickness of about 2 mm. The steel bar temperature is kept to -13°C, and the water temperature is about 20°C during this process. The ice is constructed in the evening one day before the measurements are taken. The ice is kept for one day of measurements only, after which it is removed and a new layer constructed for the following days' measurements. It is imperative that this routine be adhered to, as ice aging for more than one day has proved to affect ice friction. Since brake tests with studded tyres destroy the ice, it is not possible to conduct that many brake tests before the ice cannot be used anymore. For the bicycle tyres it was possible to divide the ice track into 7 parallel lanes to maximise the number of tests that could be performed.

Both braking and steering were considered important. Since steering a bicycle often results in a camber angle, tests should be performed both with and without camber. Brake forces are measured while continuously increasing the amount of wheel slip, from free rolling to completely locked wheel. For car tyres the peak friction, usually occurring at 5-10 % wheel slip, is of primary interest, since ABS brakes (smart braking systems) can keep the wheel from locking.

For a bicycle tyre, brake performance and stability are probably limited by the friction level with a locked wheel. Table 1, below, shows the bicycle tyres tested.

Table 1. The tyres tested on ice in VTI's tyre test facility.

Tyre id.	*Brand/model*	*No. of studs*	*Description*
D1	*Cheng Shin*	*0*	*Reference tyre, non-studded*
D2	*Biltema*	*120*	*Cheapest tyre*
D3	*Nokian Hakka Suomityre W240*	*240*	*Most expensive tyre*
D4	*Nokian Hakka Suomityre W106*	*106*	*Similar to D3, but fewer studs*
D5	*Schwalbe Maraton winter*	*240*	*Similar to D2, but another brand*
D6	*Nokian Hakkapelitta*	*0*	*Non-studded*

During one day's testing, one brake and steer test, with and without camber angle, could be performed for each of the six tyres, using separate lanes for each tyre. Tests continued for three days, using different lanes each time for a specific tyre. The testing order of the tyres was also changed from day to day, to allow for possible ice-aging effects. For each tyre, this resulted in three brake and steer measurements, each performed on different days, in different lanes and at different times of day. A certain variation is thus expected, and a larger number of repetitions would naturally be welcomed, to facilitate statistical evaluations when comparing the different tyres. This, unfortunately, was ruled out by funding constraints on this project, which must be regarded as a pilot project defining a useful methodology for comparing the ice grip of different bicycle tyres. Even so, the difference between studded and unstudded tyres turned out to be so great that meaningful conclusions could be drawn despite the small number of measurement repetitions.

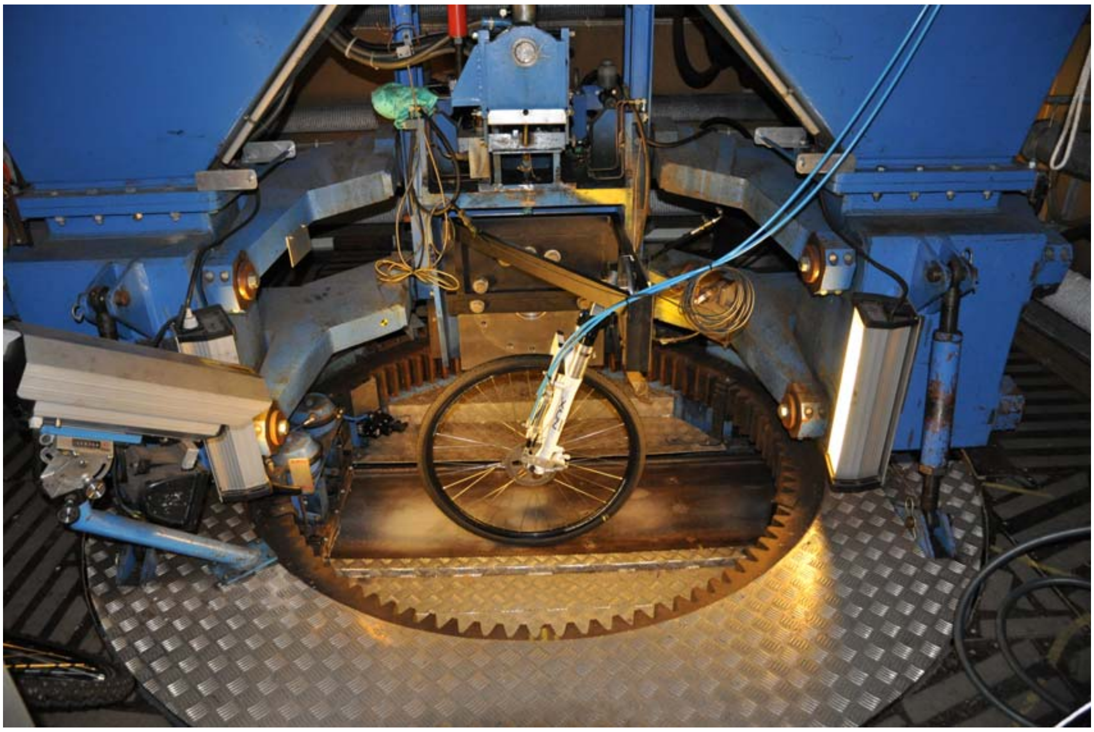

Figure 3. The VTI tyre test facility during a test of bicycle tyres.

3 RESULTS

3.1 The variation of skid resistance on cycleways during winter

The first friction measurements on cycleways during winter were conducted in Linköping in 1999 and 2000, in the PhD project [4, 11]. Those measurements showed that PFT friction values could be used to distinguish between different road conditions (Figure 4), even though the friction values for one road condition varied to some extent between different measurements, and also within one single measurement [11]. The grouping of different road conditions was based on a classification used when monitoring road conditions by visual inspections of cycleways [13].

When winter road conditions vary a lot along a cycleway, so will skid resistance. This was clear from a measurement of friction performed in Stockholm in the winter of 2013/2014 (Figure 5) [8]. On that occasion we measured a 115-metre-long section of a separate cycle path where salt had been used for de-icing. Two consecutive measurements showed almost exactly the same variation, indicating that the repeatability with the PFT is really good (Figure 5). It may seem strange that friction coefficient values greater than 1.0 were recorded. It is commonly supposed that friction never can exceed unity, but this is not true. It is not uncommon for good summer tyres on an asphalt pavement surface to produce friction levels in excess of 1.2, and in car racing friction levels much higher than that can easily be achieved.

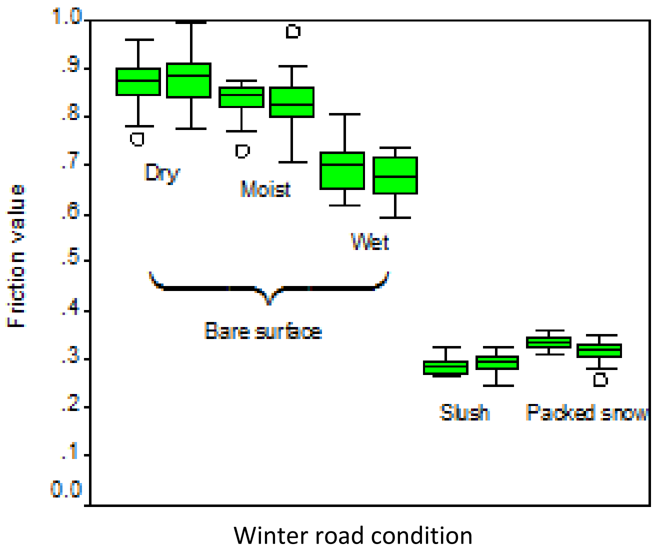

Figure 4. Boxplots illustrating measurements of friction performed with the PFT in different winter road conditions on cycleways [11]. In the boxplots, the centre half of the data, extending from the first to the third quartile, is represented by a rectangle and a line across the box indicates the median. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers (shown as circles in the figure) and extreme cases.

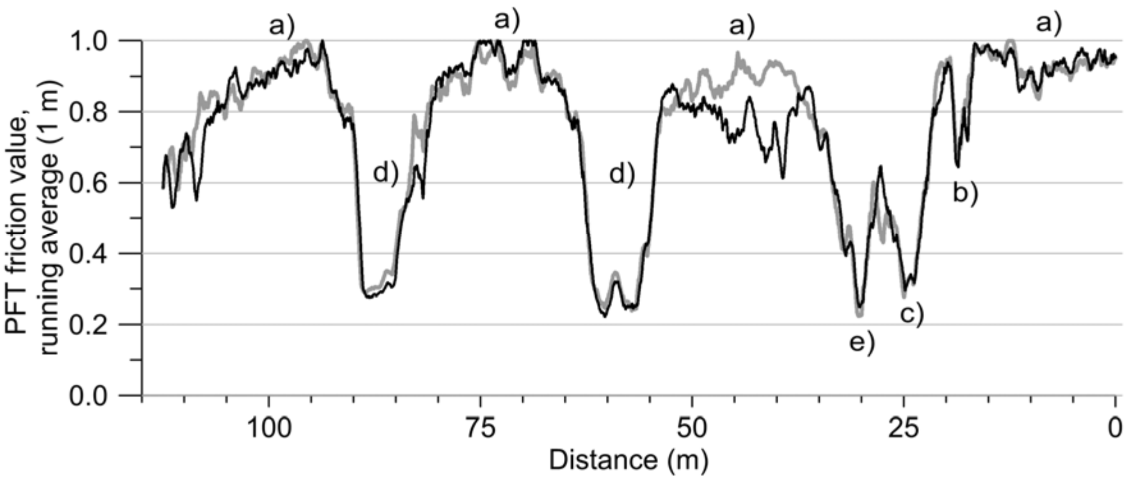

Figure 5. The PFT friction values measured twice along a 115-metre section of a cycle path where salt had been used for de-icing. Black and grey lines show friction data filtered by 1 m running average filter from two consecutive measurements.
a) Undisturbed salted sections
b) Road markings (bicycle symbol)
c) Crossroad between salted and unsalted paths
d) Crossing with roadway (red painted)
e) Icy patch on the path (due to damage of the pavement surface).

Although there was a great variation in the friction values recorded on the cycle path where salt had been used for de-icing, the mean friction was significantly higher than that on an adjacent cycle path ploughed and gritted for skid control (Figure 6). On the grit-treated cycle path the most frequent friction value obtained was 0.3 as against 0.9 on the salt-treated cycle path. Friction values around 0.3 probably representing a slippery surface.

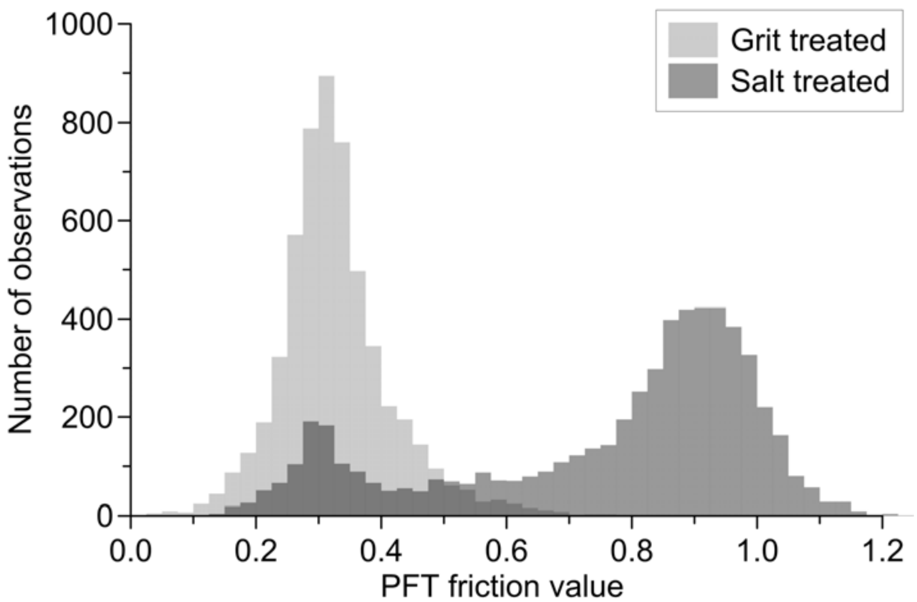

Figure 6. A histogram showing the variation/distribution of PFT friction values measured on a cycle path where salt had been used for de-icing, compared to a cycle path where grit had been used for skid control.

The winter maintenance method using salt for de-icing creates a bare surface (when working successfully) and, not surprisingly, generates higher friction values than a method resulting in a snow-covered surface with grit on. Friction measurements from Umeå in 2012 also showed that the friction values resulting from a skid control action vary according to the gritting method used [9]. A method using warm wetted sand for skid control is more effective, resulting in a higher friction improvement for a longer duration of time than a traditional method using dry sand (Figure 7). When spreading warm wetted sand, the sanding material is mixed with hot water and the sand adheres to a cold surface through a process of melting and freezing which improves the durability of the method. This method is particularly useful on sections with on-street-cycling where the road condition is more often thick ice and the wiping and polishing effects of traffic make other gritting methods very ineffective [9].

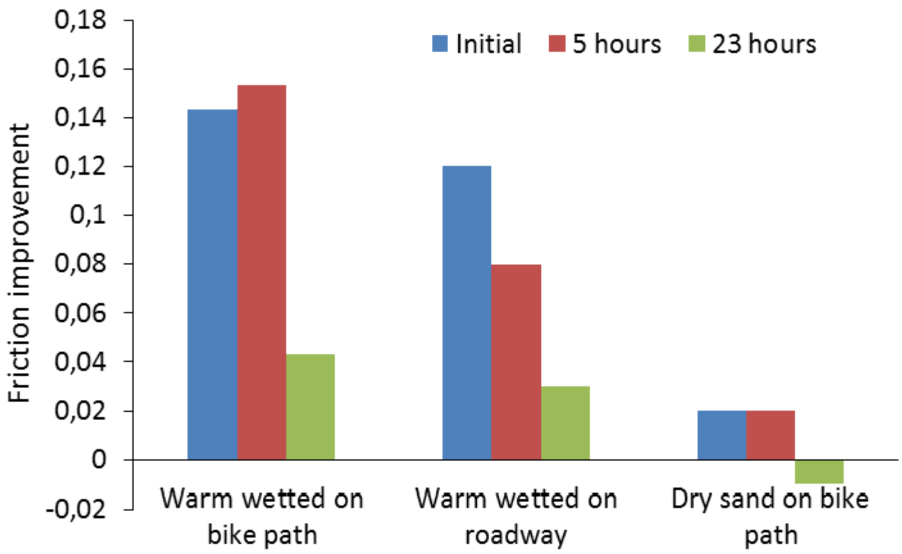

Figure 7. The friction improvement resulting from skid control using warm wetted sand on a cycle path and on a roadway with bicycle traffic, compared to the friction improvement from skid control with dry sand [9].

Figure 8 shows the PFT friction values recorded immediately before skid control actions with warm wetted sand on a cycle path, right after the actions and then how the friction value decreases with time. A skid control action – when grit is applied to the surface – results in an increase in friction value. In time, the grit becomes embedded in loose snow on the surface and then the friction value drops until the next skid control action is taken.

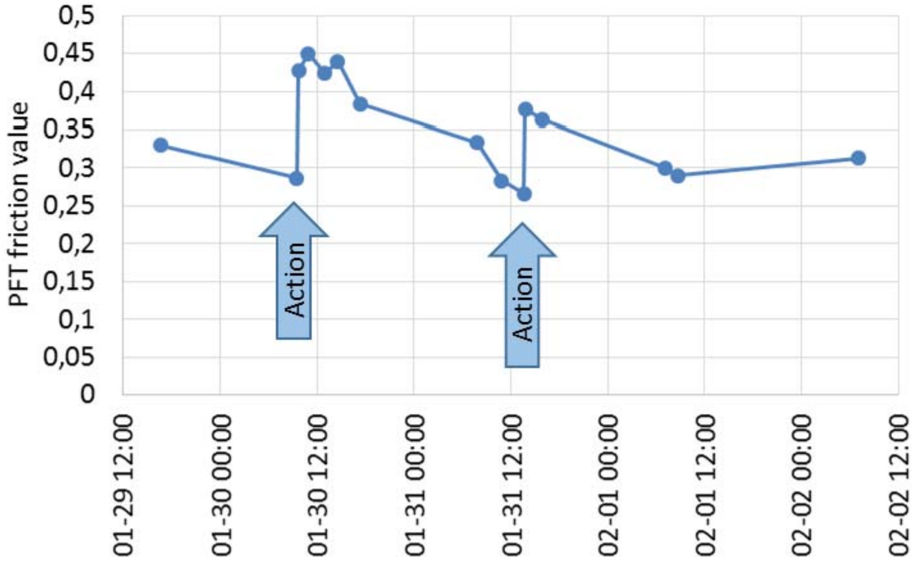

Figure 8. The increase in PFT friction value with skid control actions using warm-wetted sand on a cycle path, and the decrease in friction value (with time) after the actions.

3.2 Friction on inlet covers, road markings and red-painted coat in crossings

The measurements presented in Figure 5 showed a great variation in friction values. One measurement can be divided into subsections according to the level of friction. Where the salted cycle path was “undisturbed”, the level of friction was high (caption a in Figure 5), but where an unsalted path was crossing the friction level was low, due to slush resulting from snow transported by cyclists and pedestrians from the unsalted path (caption c in Figure 5). One damaged spot in the pavement surface, resulting in insufficient snow clearance and thereby creating an icy patch on the path, was also found to have significantly lower friction values (caption e in Figure 5).

What is more surprising is the even lower levels of friction measured where the cycle path crosses a roadway (caption d in Figure 5). In the crossing there was a red-painted coat of fine-graded mastix, similar to thermoplastic road marking material. Similar measurements performed in Linköping in summer conditions did not show any significant difference in the friction of red-painted coat in a crossing [11]. In winter, the low temperature in combination with the polishing effect of car traffic probably contributed to the low friction. Road markings – in this case bicycle symbols (caption b in Figure 5) – also showed a significantly lower skid resistance than the surrounding road surface of asphalt.

Another road design feature worth mentioning is metal inlet covers. There were several inlet covers in the middle of one of the cycle paths in Stockholm where we carried out friction measurements in 2014. There was a clear drop in PFT friction values when passing each inlet cover (Figure 9).

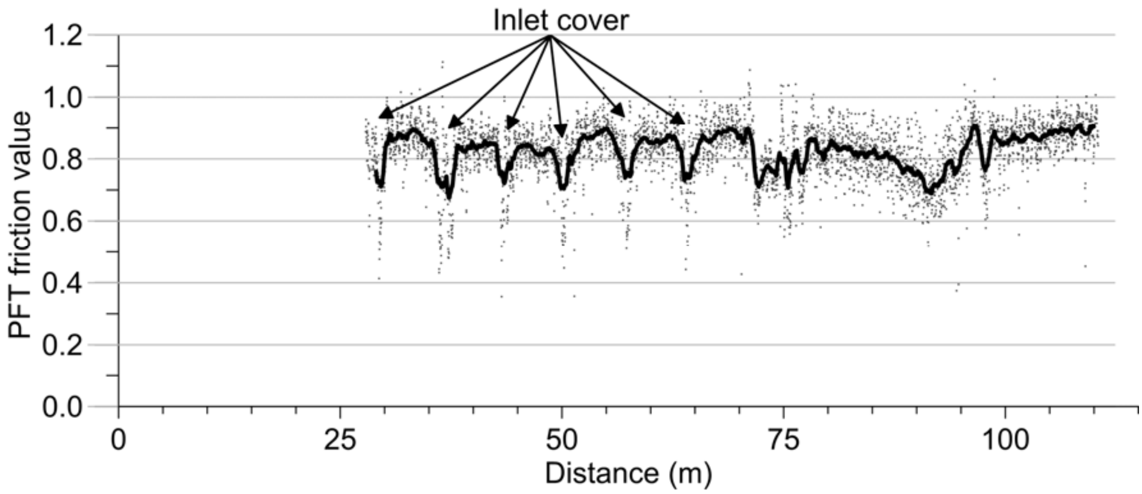

Figure 9. The PFT friction values along a cycle path which includes 6 metal inlet covers. Grey dots show each recorded friction value (approximately 2 cm spatial resolution). The black line shows friction data filtered by a 1 m running average window.

3.3 Friction on different types of paving materials

Measurements in Stockholm (in February 2014) on different types of paving materials, shows that both concrete slabs and paving stones afford lower skid resistance than asphalt (Figures 10 and 11). At the time of the measurement the air temperature was -1°C and the road temperature varied from +1 to -3°C but there was no frost or ice on the surfaces. There was no difference in mean friction value between the concrete slabs and the paving stones – it was 0.66 for both surfaces compared to 0.91 for the asphalt surface. However, the variation in friction was greater for the paving stone representing a wider histogram in Figure 10.

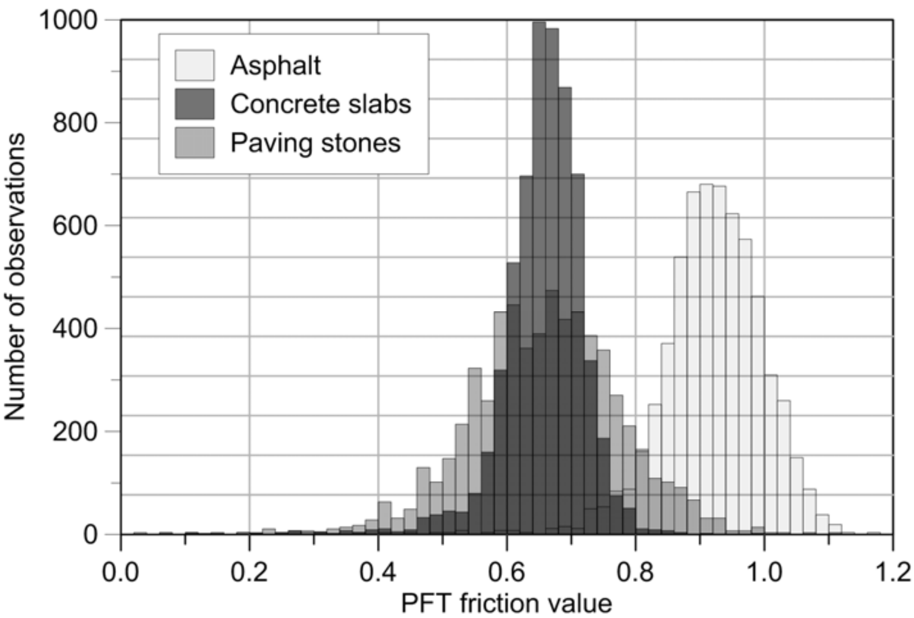

Figure 10. A histogram showing the variation/distribution of PFT friction values measured on different paving materials in Stockholm in 2014.

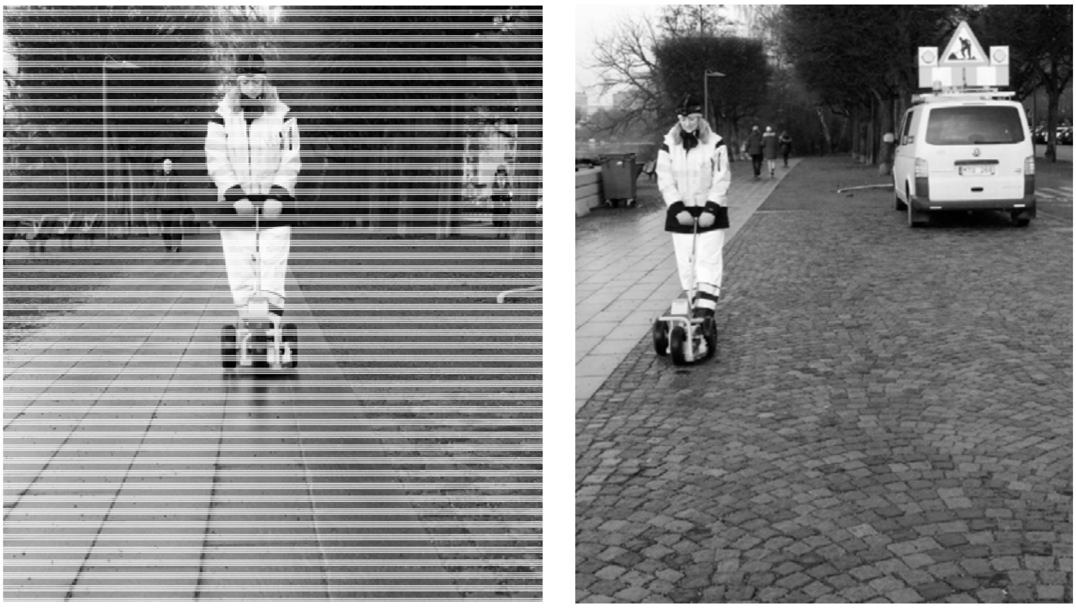

Figure 11. The concrete slabs (to the left) and the paving stones (to the right) measured in Stockholm in 2014.

Another measurement in Linköping also showed that different paving materials afford different friction (Table 2). On this occasion measurements were taken one winter morning, after a night of frost. The different surfaces were situated within 100 metres of each other, which means that preconditions, e.g. of local climate, were the same for all. At this time there was hoar frost on the concrete slabs and the paving stones but not on the asphalt surface.

Table 2. PFT friction values on cycleways of different pavement material one morning in march 2006, in Linköping.

Material	*PFT friction value*
Concrete slabs	*0.26*
Paving stones	*0.31*
Asphalt	*0.68*

3.4 Friction measurements on ice with studded bicycle tyres

Tests were carried out in the VTI tyre test facility on smooth slippery ice (ice temperature -3°C) using two regular (non-studded) bicycle tyres and four studded tyres of different brands and models. Preliminary results indicate that there can be a very big difference in ice grip on smooth slippery ice between non-studded and studded bicycle tyres. For locked wheel, which is the most relevant situation, the non-studded tyres produced a braking friction of around 0.05. In comparison, the studded tyres could have a braking friction level 2-3 times higher. Going from a friction of 0.05 to 0.15 may not seem to be much of an increase, but in reality this represents a huge difference in grip. The braking distance is inversely proportional to the friction coefficient, and for cars, which have been much more studied than bicycles in this respect, it has been shown that the accident rate increases exponentially when the friction is lowered [16]. Whether this is also true for bicycles remains to be seen. Although only three measurement repetitions could be performed with each tyre (and hence no meaningful statistical analysis could be conducted), there seems to be a wide spread of performance among the studded tyres tested. Further analysis will be needed, however, before decisive conclusions can be drawn.

The lateral friction force during steering also benefits from studs. The increase in friction seems to be around 50 per cent compared to the non-studded tyres.

No friction measurement has so far been carried out with the tyres on a bare pavement surface. For cars, studded tyres generally give just as good grip as unstudded winter tyres on bare roads, and accident statistics have failed to show any difference in accident rates between studded and unstudded winter tyres on bare road conditions [17]. Whether this also applies to bicycles needs to be investigated. In addition, these studies should be supplemented with research regarding the rolling resistance of different types of tyres on different road surface conditions, given its importance for the comfort and accessibility of cyclists.

4 DISCUSSION

4.1 Skid resistance for cyclists during winter

The fact that certain road design features such as red-painted coat in crossings, road markings and inlet covers as well as certain pavement materials afford lower skid resistance than asphalt is probably already known to cyclists and road keepers. But the studies summarised in this paper further emphasise the magnitude of the problem – the large number of skid-related bicycle accidents, and the significantly lower friction values that can actually come about on these surfaces, especially in the wintertime. Therefore, road markings and red-painted coat in crossings should only be used after careful consideration. The purpose of the red-painted crossings is to raise the awareness of car drivers in order to enhance safety of cyclists, but the effectiveness of this measure can be questioned. Shepers et al. have concluded that it might even have an adverse effect of the safety of cyclists, due to risk compensation [14]. Cyclists travel at lower speed and have a higher view of a crossing compared to car drivers, and therefore the red paint becomes obvious to a cyclist, while drivers might not see it at all. In addition, Nygårdhs et al. have shown that drivers detect cyclists before they notice the actual cycle crossing [15], which might suggest that the red paint does not help to raise the drivers' awareness. Further studies are needed regarding the pros and cons of red-painted coat in crossings, so as to arrive at a more comprehensive understanding of when and where to use it, and also to find the best alternative paving method.

Metal inlet covers afford lower skid resistance when wet and even more so during winter when temperatures are low. Measurements of friction, in Stockholm, showed a clear drop of friction when passing the inlet covers placed in the cycle path. On the spot, cyclists were seen to avoid these inlet covers. Besides being slippery, they were uncomfortable to pass since they also caused a difference in height. At peak hours with high traffic flows, this evasive action might cause conflicts between cyclists, and when covered with snow the inlet covers would be difficult to see, creating a hazardous situation if they are slippery.

The great variation in skid resistance due to winter road conditions, indicates how important winter maintenance methods and strategies are in reducing the number of skid-related bicycle accidents. Not only the friction improvement but also the durability of skid control actions taken defines effectiveness. Methods using salt for de-icing usually provide a higher friction level than methods using grit for skid control. However, methods including salt are more demanding, requiring good weather forecasts and a higher alert, and should not be used at temperatures below -6°C (according to the Swedish standard requirements for winter road maintenance). Precipitation will dilute the salt and in combination with low temperatures cause the surface to freeze. This can also be the case when run-off water flow over a cycle path or when water puddles appear on an uneven surface. Slippery patches on a surface with generally good friction might be more dangerous than a surface with low friction all over. On the other hand, when also considering the accessibility and the comfort of cyclists a surface with generally good friction might be preferred. The bicycle tyres are of course also important, and promoting the use of studded tyres in winter could help to reduce the number of skid-related accidents.

4.2 Relating PFT friction values to the performance of a bicycle tyre on a road surface

Our experience using the PFT for measurements of friction on cycleways is that the instrument is well suited for that purpose. The repeatability between two consecutive measurements is good and it is easy to collect data to distinguish two different surfaces from one another. This is particularly valuable for comparing measurements. One problem, however, is how to relate the observed PFT friction values to the skid resistance between a bicycle tyre and a particular road surface. This means that a link is missing in order to make statements regarding the absolute skid resistance for cyclists. Further studies are needed in order to define the PFT friction values that represent a slippery surface from a cyclist's point of view.

According to the Swedish standard requirements for winter road maintenance, friction values below 0.25 define a slippery surface. That is valid for measurements performed with a Saab Friction Tester. Earlier studies have indicated that the PFT friction values are comparable with those measured with the Saab Friction Tester [10]. However, the definition of a slippery surface is based on the performance of a passenger car, which is of course not directly transferable to the performance of a bicycle. In addition, the requirements represent a mean value over a 20-metre section. For the safety of cyclists, that mean value is of little interest since it only requires a small slippery patch for a cyclist to lose their grip. Therefore, the minimum friction value might be more interesting to measure and present. However, it can be questioned how large a slippery patch has to be to constitute a danger to cyclists. The PFT records a friction value approximately every 2 centimetres, and the variation in friction between each single measurement is significant (see the dots in Figure 9). We have used a one-metre running average window to even out this variation. It is reasonable to exclude extreme values, but where the limit should be set is a debatable point.

Relating PFT measurements to the performance of a bicycle tyre on a road surface is complicated. PFT measurements are performed with a different type of tyre, at very low speed, and using a peak friction value. Typically, a bicycle tyre is quite different from the PFT tyre, the speed is much higher and for braking in slippery conditions it is the locked wheel friction that is of most importance. The PFT could still be an excellent tool for measuring friction, and should be relevant for bicyclists even if relevant friction levels for bicycle tyres cannot be determined.

To set an absolute value representing a slippery condition will be difficult anyhow, since the skid resistance will vary with the type of tyre, the tyre pressure – and for studded tyres also the type and number of studs – as well as other tyre characteristics. The speed and skill of the cyclist is also important, as well as bicycle stability.

5 CONCLUSIONS

Accident analysis has made clear that skid resistance is an important factor for the safety of cyclists. It is also important for their travel time, their comfort and their decision whether or not to go by bike. From the measurements of friction on cycleways presented in this paper we can also conclude the following:

- There is a great variation in friction on cycleways in winter, depending on the winter road condition, which is related to the winter maintenance method used.
- Friction also varies with the pavement material.
- Design features such as inlet covers, road markings and red-painted coat in crossings result in a significant reduction of friction during winter.
- Studded tyres improve the grip on ice compared to regular tyres both when steering and braking.
- There is a difference in grip between different types of studded tyres.

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