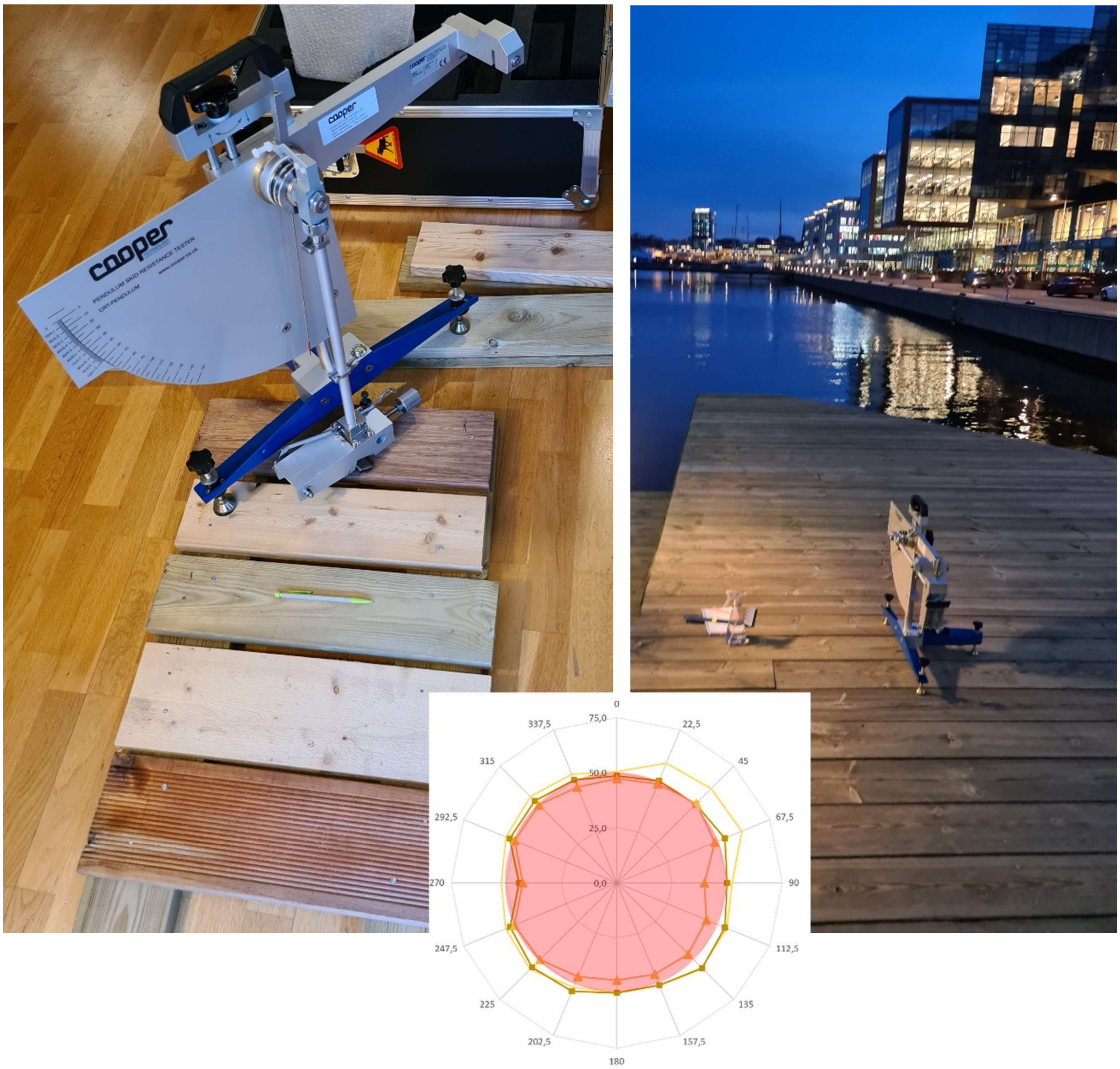
ModC Networks
Cycling infrastructure

Skyltfonden – TRV 2021/21799 – Final Report
Practical friction coefficient on wood for unprotected road users.



Dokumentinformation

Titel: Praktiska friktionskoefficienter mellan trävägar och oskyddade trafikanter

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Foreword

We present below the final results of our project "Practical coefficients of friction between wood and unprotected road users".

The final report has been produced with financial support from the Swedish Transport Administration's Skyltfonden. Positions, conclusions and working methods in the report reflect the author's views and do not necessarily correspond with the Swedish Transport Administration's positions, conclusions and working methods within the report's subject area.

ModC Networks AB (Modular Cycling) develops modular cycling paths in wood. During the company's product development, many questions have arisen about friction on wood that could not be answered with the available literature. The work presented below is a step towards a better understanding of this scientific field and an attempt in contributing to better road safety for unprotected road users.

Foreword to the English version

This is Modular Cycling's own translation with help of Google Translate©.

If any part is unclear or lacks logic, please refer to the Swedish version or contact us.

Summary of the project

We have, with the support of the Skyltfonden (Road safety research fund), explored the properties of different wooden surfaces in terms of friction in a walking and cycling context.

We have developed a new method which, despite limitations regarding HSE aspects, has provided useful information and demonstrated that bicycle tires have good friction properties perpendicular to the direction of travel even on slippery surfaces.

We have chosen to use the British Pendulum Test, or Skid Resistance Tester (SRT), an established method for measuring friction between rubber tires and different surfaces, to evaluate the selected materials.

We have performed about 1500 manual measurements that give a complex picture of the wood substrates' friction properties and pave the way for further research on - and development of - "wood pavement".

The grain direction influence on the friction properties of wooden substrates is confirmed and put in a new light as today's widely used installation direction turns out to have the worst friction of all angles in many cases when looking at lateral stability.

Moisture content management, a traditionally important aspect for constructive design of wooden structures, mainly for reasons of durability, is reinforced by the observation that the moisture ratio also affects friction to a negative extent. Therefore, the moisture management of all wooden pavements is an important prerequisite for a safe active mobility path in wood.

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1. Background

The background knowledge in Sweden is best described in VTI reports 952, 980 and 993. Also [5], [16] and other references provide good information regarding the subject. It clearly shows that today there are no special standards for minimum friction value and friction measurement for active mobility paths in Sweden.

Also [14] shows that the scientific basis for explaining friction between a rubber tire and a surface is not completely determined and that there are an incredible number of parameters that play a role, e.g. road and tire temperature, amount of liquid water and / or contaminants, type of rubber and its pattern, air pressure, dynamic effects, wear…
When we introduce wood, instead of much-researched asphalt, the situation is further complicated, mainly due to 3 things. First, wood has different textural properties depending on which direction you study (anisotropy). Secondly, wood is hydrophilic, i.e. it interacts actively with water both in liquid and vapor form, with varying properties as a consequence. Finally, wood has less resistance to the growth of various algae and plants that develop over time over any surface, but which can lead to impaired friction when associated with water.
We have not seen that there is generally available information regarding wood friction properties in a traffic safety context. Although wood is widely used as a base for patios, cycling bridges, etc., wood has a bad reputation when it comes to friction. The report presents some results that begin to answer why it can be so.

Usually, most measurements focus on the friction area with 15% slip where maximum friction occurs. However, it is friction at 100% slip that most determines when a bike will lose control and start to slip uncontrollably sideways, leading to a loss of balance and possibly the fall of its rider.

Therefore, we have tried to develop a technique for measuring friction in this area under realistic conditions. During the work, however, we have discovered that the new method was dangerous to use (a 20 kg weight in free fall contains a lot of energy) and that the friction force was actually very high which means that, even with smooth tires on surfaces with low friction (smooth wet concrete, SRT number about 30) the lateral frictional force was significant leading to the measurement being dominated by dynamic effects controlled by the rigidity of the wheel-frame arrangement rather than friction itself.

For that reason, we have instead chosen to continue working with an established method, the British Pendulum Test, or Skid resistance Test (SRT), which is a well-proven method and has been used for a long time in Sweden, and is still used for example to measure friction on road markings (Trafikverket 2013, Vägverket's metodbeskrivning 1987: 142) where the SRT number must exceed 50 (previously 45) to provide safe conditions for traffic, see Figure 1.

SRT is also a method that looks at friction at 100% slip as a rubber block is swung towards the surface to be measured and pressed down against it with the help of a spring. It is portable and can be used both in the field and in a lab. In addition, the system is harmless as the pendulum's weight is very limited.

The measuring surface of 125x75mm is small enough to enable the measurement of smaller wood samples taken from planks and boards commonly used as pavement material.

Friction in a cycling context

Most friction measurements in a road safety context are designed primarily for motor traffic, i.e. large, fast four-wheel vehicles that circulate on paved surfaces.

It is well known that the dynamical friction coefficient varies with the amount of slip, and most measurements are made where it is closer to its maximum, i.e. the 15% slip range.

Pedestrian-specific measurements are also made, mainly in connection with flooring development and control.

Cycling requires a third point of view of the friction properties for various reasons:

- As a two-wheeler, the lateral friction properties are crucial as exceeding the maximum allowable lateral force often leads to a crash (a car remains stable even with lost steering ability, and can also use engine power to improve steering).
- The contact surface between the bicycle tire and the road surface is smaller and different as the bicycle tire is a torus vs a more cylindrical car tire. The tire pressure is also usually greater for a bicycle.
- Due to the cyclist's lower speed and low total weight, braking problems loose importance, steering and lateral stability become the most important safety situation involving road friction.

Previous research from, among others, Dressel [10] has shown the complexity of the contact surface between a bicycle tire and a flat surface, as well as how its contact parameters can vary (See below). This means that it is not possible to simply and unambiguously describe the complex interplay that friction entails. But it is nonetheless possible to create a framework for understanding the probable behavior in practice and supporting the development of safe infrastructure.

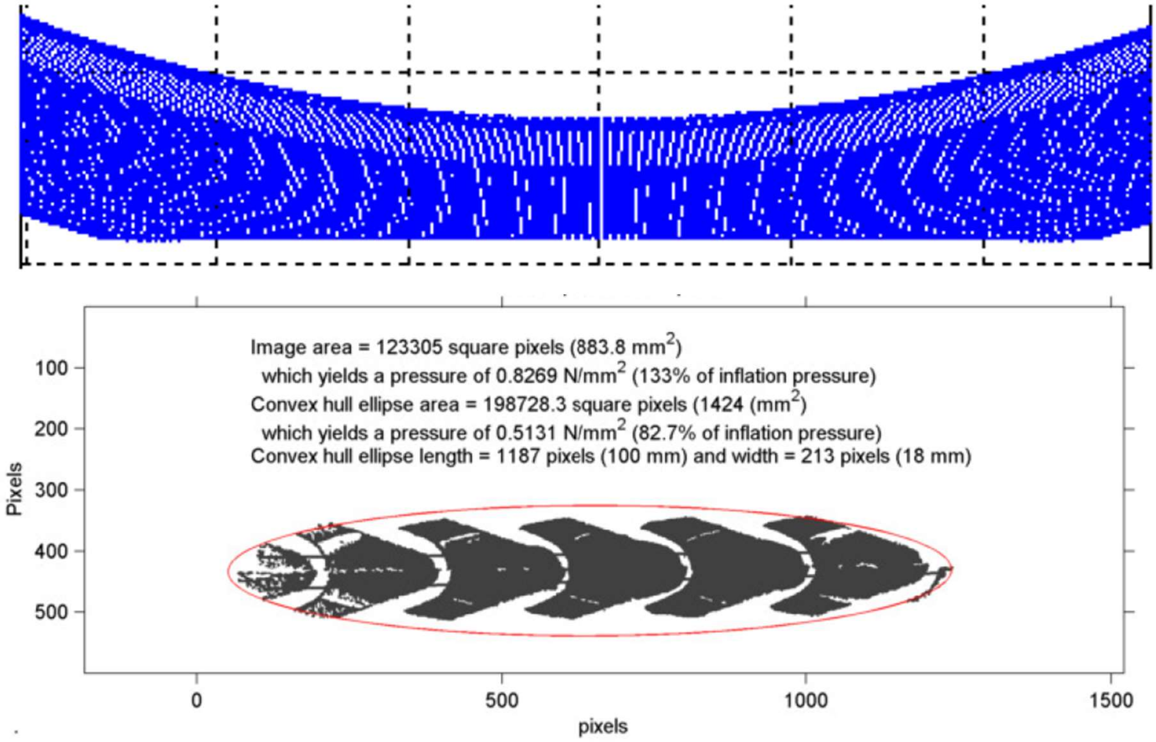


Figure 1: Top: Torus-shaped bicycle tires in contact with the road. Bottom: Typical contact area between a bicycle tire and a flat surface. Both from Andrew Dressel's work [10] with his kind permission.

Steer angle's influence on friction angle

It is established that a bicycle needs friction in mainly two directions, which for most practical conditions and speeds coincide with the main directions of a road (longitudinal and transverse). At the same time, steering and the permanent balancing exercise that cycling entails dictate that the steering angle (angle between the plane of the front wheel and the vertical plane of the bike) varies permanently and therefore affects the angle between the bicycle tire and the wood fibres of an hypothetical wooden surface on which it is riding.

Moore [28] has investigated several parameters from real cyclists, including the steering angle. The result shows that for speeds above 5 km/h, the steering angle is usually below 3 degrees. This means that we can assume that if a wooden pavement is built with the grain rotated at a certain angle to the expected direction of travel, the overwhelming majority of the frictional interactions will take place within a few degrees from the two main directions and that an optimization of this grain angle can lead to significant improvements in practical friction properties for cyclists, taking into account the wood's anisotropical friction properties.

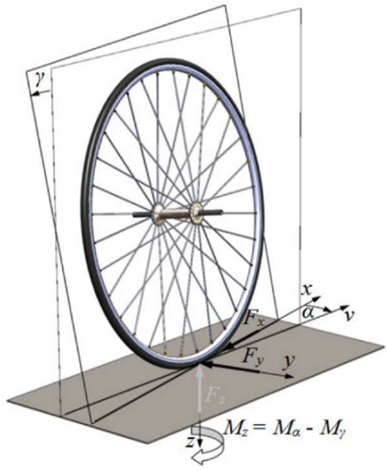


Figure 2: Dynamic model of a front bicycle wheel [10].

Figure 3: Examples of wheel tracks at 100% slip (hard braking) and slippery surfaces.

Left: Non-studded tires on contaminated, wet wood.

Right: Studded tires on ice.

Initially, the frictional force acts against the direction of travel of the bicycle, but when the cyclist tries to steer and balance away from freefall, the wheel is pushed sideways overcoming allowable lateral force leading to a fall.

Under pure steering conditions, the wheel track would look different, but this is a riskier experiment.

2. Project goals

This project had two major ambitions:

a. Reduce slippage-related accidents on wood-covered surfaces by creating new knowledge
b. Enable a more widespread construction of wood-covered infrastructure, through an improved understanding of friction on wooden surfaces,

The purpose of the project is to prove that it is safe and useful to build pedestrian and bicycle paths in wood, providing safe design guidelines. Cyclists and other unprotected road users today belong to the most vulnerable group in traffic. Their share of the number of injured in traffic has increased, and they have not benefited from the general increase in traffic safety that Sweden has seen in the last decade.

In spite of this, it is important that the modal share of walking and biking increases in order to achieve Sweden's Climate Goals. Such development is also associated with major health benefits, and contributes to a more attractive urban environment, as it creates more interactions between people, greater demand for local trade, and nicer traffic configurations with better air quality etc.

A key factor in protecting pedestrians and cyclists is to deliver dedicated infrastructure with good frictional properties in all weather conditions.

There are many parameters that play a role, and therefore it is difficult to determine a unique friction value even for a single patch of path. Consequently, there is a general lack of friction data to support road safety, especially with regard to unprotected road users and wooden surfaces.

As a consequence, the most common accident[1] for both pedestrians and cyclists in Sweden is a single-person accident, with slippery conditions cited as the most prevalent contributing factor.

Therefore, we have carried out the project to look at how to measure practical friction coefficients for different types of unprotected road users and to start compiling a database of such parameters under different conditions.

[1] The most serious accidents, however, occur in collisions with motor vehicles.

3. Method and substrates

a. New measurement method

A new set-up has been developed to measure the friction of bicycle tires across the direction of travel. It built on two weighted-down bicycle wheels linked together with a shaft, being pulled out laterally by a weight in freefall. The tires where smooth Biltema tires with 4 bar pressure and 20 kg weight matching the freefalling weight.

While the method has proven to be too dangerous to use extensively, it has provided interesting data. Not least a practical proof that the bicycle tires have excellent friction properties in the transversal direction e.g. it only requires a low friction number to be able to steer a bike (probably lower than the existing requirement for friction coefficients).

b. Theoretical alternative

After it became clear that the intended measurement method (a.) Could not be used to generate the desired data, we have looked at different options.

While we performed most measurements using SRT (c.), we also want to present here a theoretical approach for a new measurement method adapted to the needs of cyclists and which could possibly be used in a similar way to established methods (rosanne-project.eu Deliverable D3.4 among others).

Several measurement methods looking at asphalt friction over long distances today consist of a system where a calibrated wheel is pulled behind a vehicle, the wheel being rotated around a vertical axis about 15 degrees from the direction of travel to generate slip. By continuously measuring the realigning torque that occur, the friction coefficient can be calculated. The method is reliable and delivers good data over longer distances. Unfortunately, the measurement is designed to reflect the dimensions and speeds of four-wheel motor vehicles.

We propose to develop a similar method where one or two bicycle wheels are pulled behind a vehicle at a lower speed (15 - 25 km/h). Instead of rotating the wheel around a vertical axis, we propose to rotate it around the horizontal, longitudinal axis so that the wheel leans in a similar way to a cornering bicycle. The wheel can be braked to achieve a certain slip ratio if desired. Wetting can be done in similar fashion to established methods.

The bicycle wheel is pressed down against the road surface with a controlled vertical force representative of a real situation.

The measurement can then be done in two different ways:

- By measuring the reaction forces that arises at the contact patch, a friction number can be calculated
- By calibrating the wheel's angle and other geometric parameters as well as vertical force, we can create a system that will start to slide sideways at a certain friction number. Such areas are the ones deemed unsafe for (cycling) traffic

The advantage is to get continuous values, adapted to the characteristics of bicycle traffic. In addition, the second option has the potential to capture the real conditions where lateral friction is not sufficient and other measurement systems are limited, such as substrates with coarse macro texture or loose gravel…

c. Skid resistance tester

The purpose of the project was from the beginning to generate friction data that is representative of real conditions between bicycle tires or shoe soles and different wooden surfaces. For that reason, we have investigated several possible established methods that could deliver such information in addition to or instead of our own method.

We have chosen the well-established method Skid Resistance Tester - SRT (C. G. GilesB. E. SabeyK. H. F. Cardew, 1965) which is based on a rubber plate swivelling against the surface being measured. The method is simple and has been studied and benchmarked many times including by the Swedish Road Administration (Trafikverket).

The configuration where the rubber plate moves against the surface means that we measure at 100% slip, which was our original ambition, while the speed range is lower than other methods and more suitable to cycling (5 m/s).

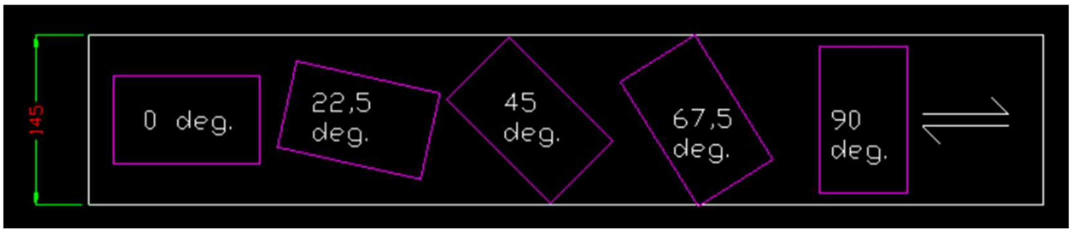


Figure 4: Illustration of the measuring surface on a plank 145 mm wide. Rounded corners and tolerances mean in practice that 45 and 67.5 degree angles often lack a small contact area in the corner. The fibre direction is illustrated by the arrows.

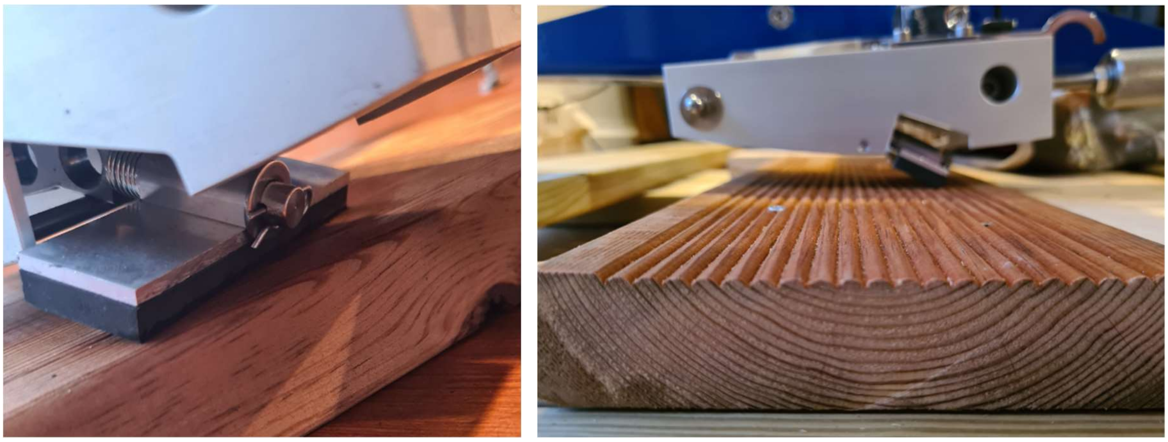


Figure 5: Illustration of the contact line between rubber plate and plank (Left) and with a grooved surface(Right)

While we explore a number of different parameters, there is one important aspect that is critical to friction on wooden substrates that is not included in this work. It is well known that biological growth on wooden surfaces can lead to a very slippery surface when wet. This growth is something that happens over time and is very dependent on the local climate, weather exposure, type of wood and choice of wood treatment as well as mechanical wear (traffic) and maintenance. There are various ways to prevent the biological fouling, and the surest way to ensure good friction over time is to sweep away the entire road surface at least a couple of times a year. This can be done for example in connection with leaf or grit removal and does not need to entail an additional cost for the road operator.

Due to the time it takes for the fouling to affect the friction, the aspect could not be included in the project. However, we have measured some existing surfaces and will continue to do so in order to generate more information regarding this effect.

SRT on wooden surfaces

There are several specificities or limitations associated with using SRT to measure friction on a wooden substrate:

I. The size of the surface being measured is limited to 75x125mm. This is positive as many planks are only 120 mm or 145 mm wide. However, a wider track is required when we start measuring for friction at angles between 0 and 90 degrees. For that reason, the measurements have focused on planks with a width of 145 mm, although some 120 mm have been measured as well. In such case, results for the angles involved may have been affected. We have always tried to set-up the measurement so that the first contact line was completely on the plank, which means that the missing surface was at the end of the measurement and therefore lead to a lower friction value than if a full contact patch had been measured. See Figure 4.

II. The measurement involves repeated rubbing of the same water-sprayed surface. This means that the surface can be cumulatively affected over the full measurement run by wear and water absorption/pooling, possibly affecting the results. This observation led us to make measurements under different moisture contents. We also chose to increase the number of "set-up runs" (oscillations without recording the measurement) from 3 to 7. The rubbing effect has been observed in our test with a 3D printed surface, see below.

III. Wood is less uniform than other covering materials due to knots etc. Geometric limitations mean that it is not always exactly the same surface that is measured. While we have tried to avoid particularly poor surfaces (resin pocket, crack, knot...) it is likely that some of the variations in the measurements originate from such aspects. It can help explain some unclear trends in the data.

Other relevant aspects not discussed here:

- Variations in effective contact length due to lack of horizontality, worn-down measuring plate, cupped plank, unsteady device
- Effect of temperature variations
- Accuracy of the set-up, including fibre angle

Finally, it can be observed that the SRT gives good and repeatable results, but that their interpretation in both cycling and walking contexts must be analysed looking at the bicycle tire and the characteristics of the shoes. For example, the wide and linear contact line has a completely different theoretical behaviour than an ellipse-shaped contact surface typical of a bicycle tire. This can particularly affect the measurements at 0 and 90 degrees. Furthermore, the stud pattern and air pressure of the bicycle tire will probably affect the friction to a greater extent than the fibre direction itself.

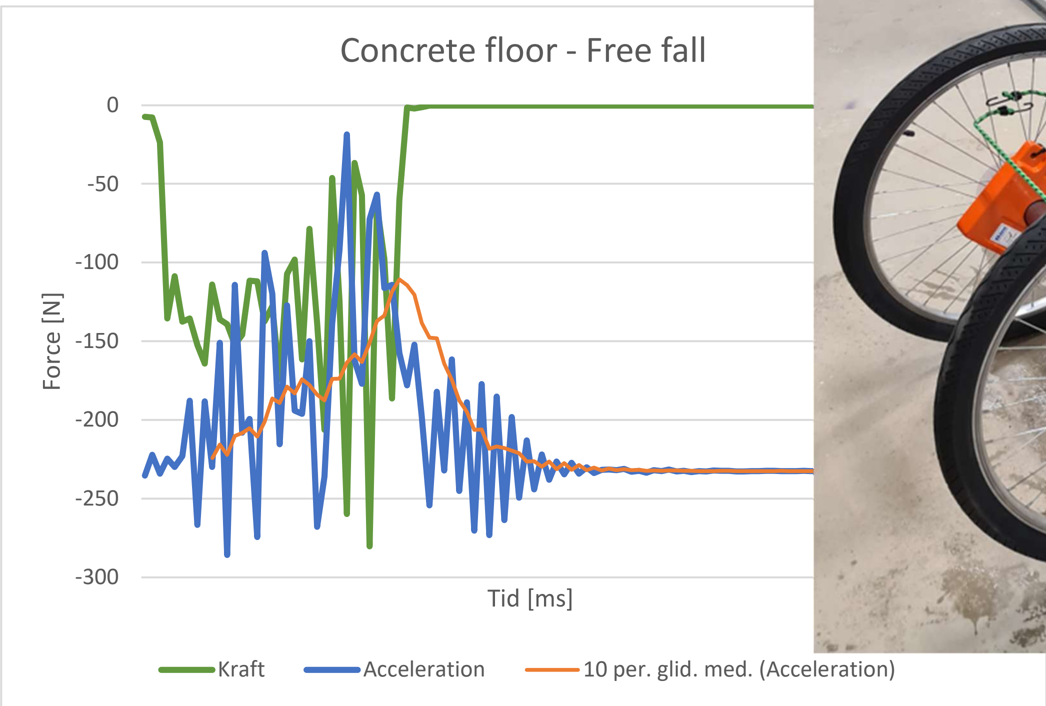
In theory, it should be possible to combine such measurements with simulations to be able to give a more accurate picture of the friction properties of bicycle tires and shoes, see f.e. (Yurong LiuT. FwaT. FwaY.s ChooY.s Choo, 2003).

4. Results

a. Own method

We developed a method to measure friction of bicycle tires perpendicular to the direction of travel. While the method has proven too dangerous to use extensively, it has delivered data, not least proof that a bicycle tire has excellent friction properties in that direction e.g. it only requires a low coefficient of friction to be able to steer a bicycle, probably lower than the existing coefficient of friction requirement.

The method involved measurements with both an accelerometer and a force meter. The result of a test run on a smooth concrete surface (warehouse floor, SRT number wet: approx. 30) is shown below. Tire pressure: 4 bar.



As is clear from the (unfiltered) results, the behavior of the wheels is very cyclical and involves a "stick-and-slip" phenomenon probably characteristic of our set-up. This is mostly governed by ratios between the stiffness of the wheel system and the available friction. The measurement time is approx. 1.6s, corresponding to a 1m drop height.

Based on the data we have, we can produce a value for the coefficient of friction. Based on the measured horizontal force, the average coefficient of friction is about 60%.

Based on the acceleration, we can suggest a value of about 15%.

It is clear that the dynamic effects that characterize the measurement have far too much influence on the results and therefore no good value can be produced.

While it would have been possible to improve the device to make it stiffer and less sensitive to oscillations, other aspects, mainly HSE issues linked to the safety of working in the vicinity of a freefalling weight of 20 kg meant that it seemed better to focus on SRT and its proven track record. Thus, further measurements with the method have not been performed.

The work has nevertheless proven that the lateral friction potential of a bicycle tire is very high as, despite the low friction value of the surface (SRT), the behaviour has been characterized mainly by high frictional resistance followed by fast frictionless sliding which is theorized to derive from the moments when the nearest wheel is dynamically lifted up and flies forward until it comes back into contact with the substrate again and stops.

b. Measurements with the Skid Resistance Tester

A wide number of substrates have been selected and are measured with SRT. The measurements can be divided into three categories:

I. Measurements of wooden substrates with a focus on the effect of fiber direction
II. Measurements of wooden substrates with a focus on the effect of moisture content
III. Measurement of other surfaces for comparison

Initially, we have focused on measurements for three angles (0, 45 and 90 degrees) but in both dry and wet configuration.

Afterwards we have chosen to measure instead every 22.5 degrees (Π/8) and only in wet configuration as the dry measurements confirmed that friction on uncontaminated wood is never a concern when it is not wet, and they generate a lot more wear due to the lack of lubrication. We have also standardized the run-in procedure by performing 7 set-up runs before 4 measurements run are recorded.

We have come up with different ways to visualize the results, and have mainly stuck to a "friction rose" that shows the average measurement value for each fibre angle.

In the results, 0 degrees corresponds to a movement of the plate parallel to the wood's grain direction regardless of growth direction. During the course of the measurements certain indications have emerged that even the planks growing direction (ie 0 for sliding in the original tree's upward direction or 180 degrees for the downward direction) has significance for the friction coefficient, due to the original trunk's naturally conical shape. This matches well with general carpentry knowledge regarding planning direction against or along the grain (higher friction being observed when planning against the grain). However, this introduces an additional variable as the effect is different depending on whether the measured surface has been sawn towards the core side or the outside of the stem, which is not always easy to determine. For that reason, we do not differentiate the aspect in our results.

All measurement values (average of 4 measurements) are reported in Appendix A.

For reference, the Swedish Transport Administration's limit of 50 is represented by a red line or a red circle (friction rose).

Effect of water film

Initially, SRT measurements were carried out in both dry and wet configurations to estimate the influence of a wet surface on the coefficient of friction.

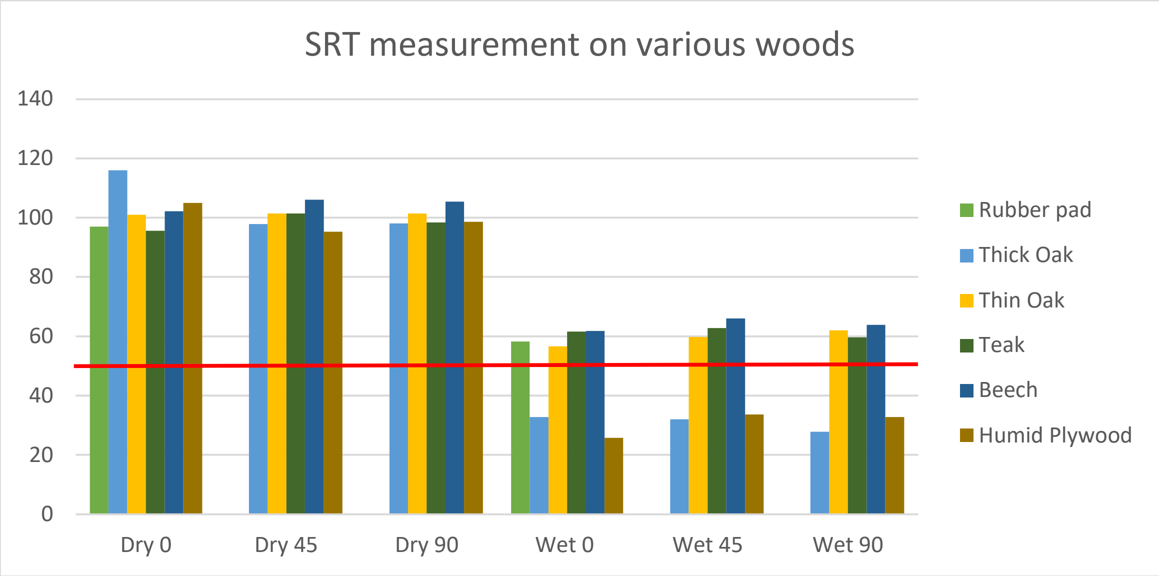


Figure 6: Effect of water film and angle on different substrates. Low values for oak and plywood are linked to a contaminated surface (Linseed oil).

As can be clearly seen, even contaminated surfaces deliver sufficient friction in dry conditions. However, the water film has a decisive effect and reduces the coefficient of friction for the illustrated materials by an average of about 50%.

The good performances of the beech sample could be connected to its very dry state (below 10% MC).

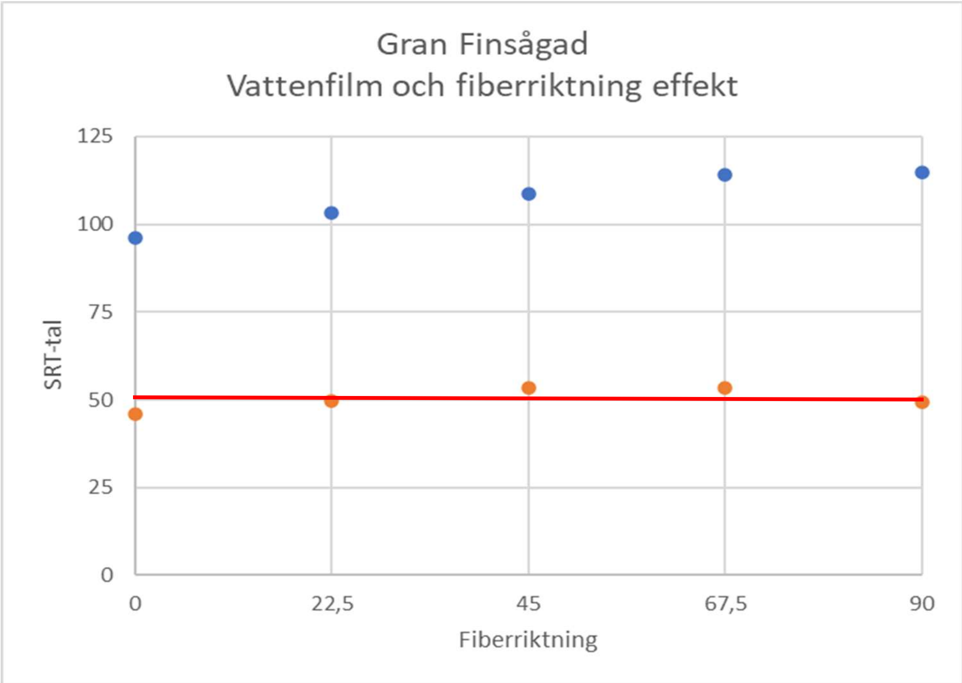


Figure 7: Effect of water film and angle for smoothly sawn spruce. Blue: dry conditions; Orange: wet conditions

Grain direction

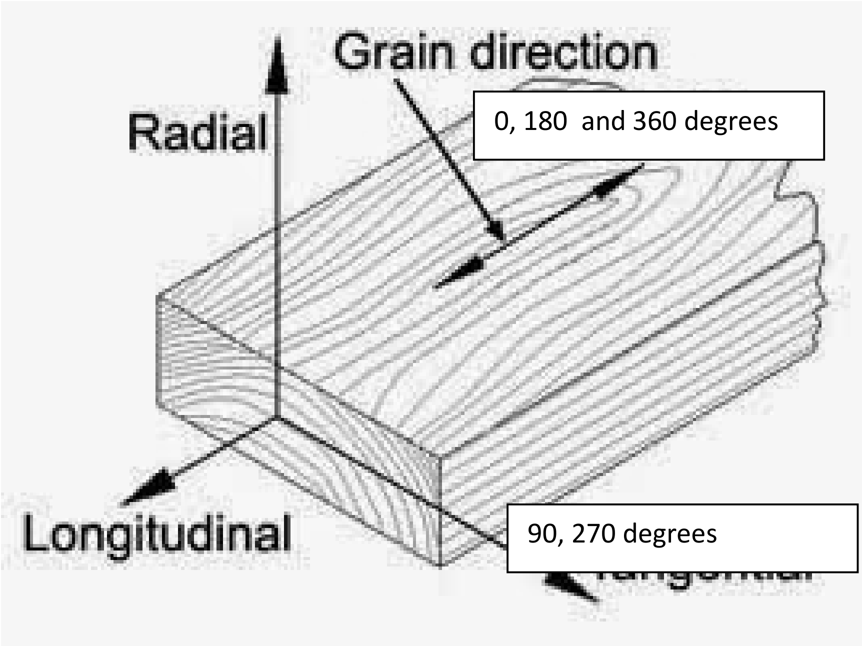


Figure 8: Fiber direction nomenclature. In addition to the above, there are also differences in the longitudinal direction depending on the angle between the fibers and the sawing plane (see Cota [26])

At the beginning of the work, the assumptions was that friction on wooden substrates was strongly anisotropic and that the dynamic friction coefficient would be higher across the grain (90/270 degrees angle) than along the grain (0/180/360 degrees).

The results show a more complex picture and the main outcome is that the intermediate angles ($\frac{n\,\pi}{4}$ or $\frac{n\,\pi}{8}$ with n odd) show the highest friction potential in most cases, especially when we consider the need for both steering and speed control acting perpendicularly to each other.

We have chosen a number of different surfaces to show as wide a picture as possible of friction on wooden surfaces. Some of it was material that we had available in our workshop, some was bought from ordinary hardware stores around Gothenburg.

As explained above, the width of the planks may be too small to provide sufficiently good measurements at certain angles. In addition, measurement conditions were not always fully controlled, especially at the beginning when the influence of certain effects (moisture content, number of test runs, ...) was not fully understood. We believe that, despite these limitations, the data has a good scientific value and can provide support for further development.

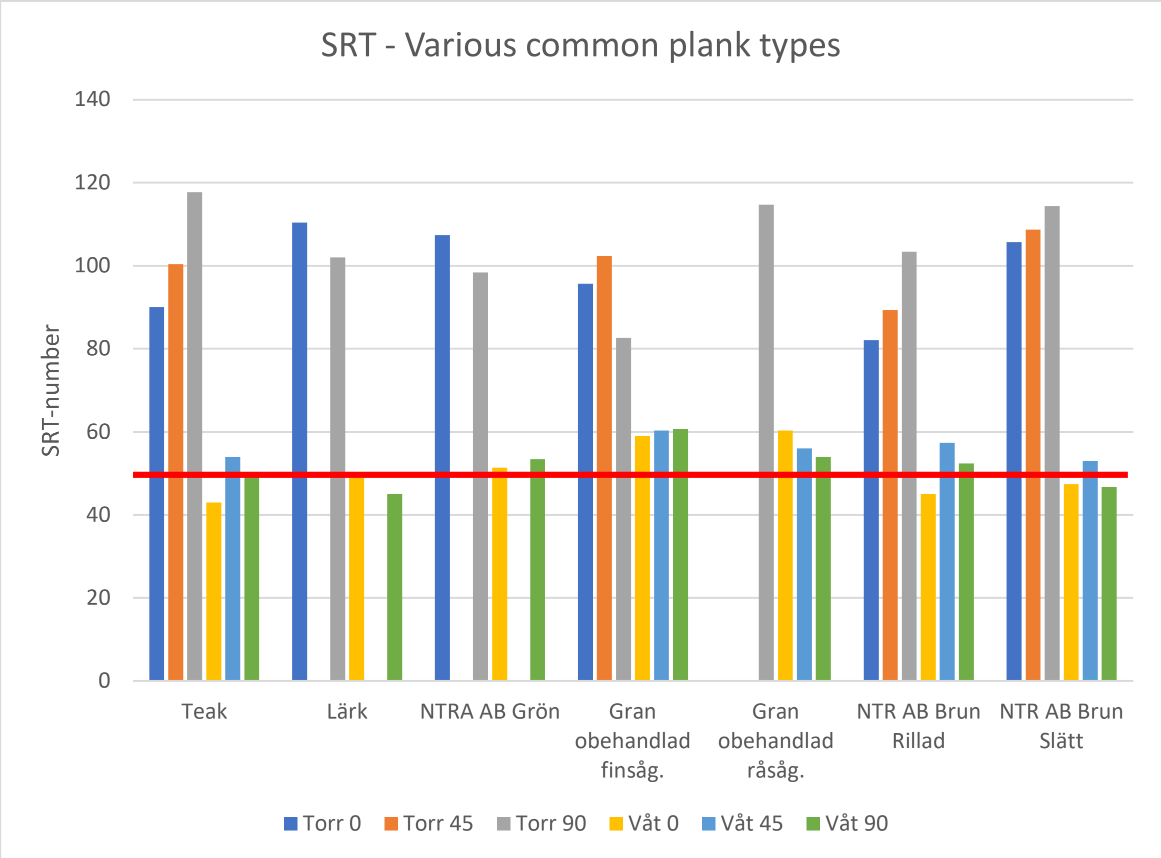


Figure 9: SRT number for different planks and fiber angle in dry (torr) resp. wet (våt) conditions

As seen in Figure 9, the grain direction of the wood has an important influence, although it is smaller than the lubrication effect of water. However, the effect is important in wet conditions as it can determine if the SRT number falls below the requirement of 50. The results above do not give a clear picture of the fibers' impact, and some planks could not be measured at 45 degrees due to their narrow dimensions. Among other things, spruce has an opposite behavior if we measure the rough-sawn side or the fine-sawn side (same board). The trend is also not necessarily the same in wet or dry conditions. In accordance with the previous conclusion that dry friction was not a problem for wood, we have focused more closely on the wet conditions. The conclusions that are drawn further down regarding effect of fiber direction must therefore be interpreted in the context of wet friction, the domain where it is most critical to achieve relatively higher friction numbers.

For that reason, we have chosen to make more extensive measurements with the planks of untreated spruce and NTR AB Brown, which is grooved and therefore could be interesting to evaluate more closely.

Figure 10 shows the influence of the fiber direction on the coefficient of friction. Surprisingly, the measurements in the direction transverse to the fiber direction are clearly lower (angles 0 and 270). This is confirmed by the sounds emitted when measuring in the direction, and could be explained by the limitations of the measurement method where the rubber plate is parallel to the fibers and thus can be affected in a non-representative way in that configuration (vibratory resonance).

It is also clear that the texture of the surface (rough cut vs fine cut) is of great importance for the friction coefficient, although traffic wear and fouling might render this effect insignificant.

Finally, we can clearly see that the highest friction number is achieved at a 45 degree angle to the fiber direction, although the detailed results show that even the range of 22.5-67.5 degrees can achieve the highest friction number for the measurement series.

In this case, the planks, placed with the rough cut upwards, and placed at an angle of 45 degrees to the direction of travel, would achieve the requirements for an SRT number higher than 50. However, the margins are small and since the plank is untreated, it can in practice not be used for outdoor structures without further wood protection treatment which will also affect its friction properties.

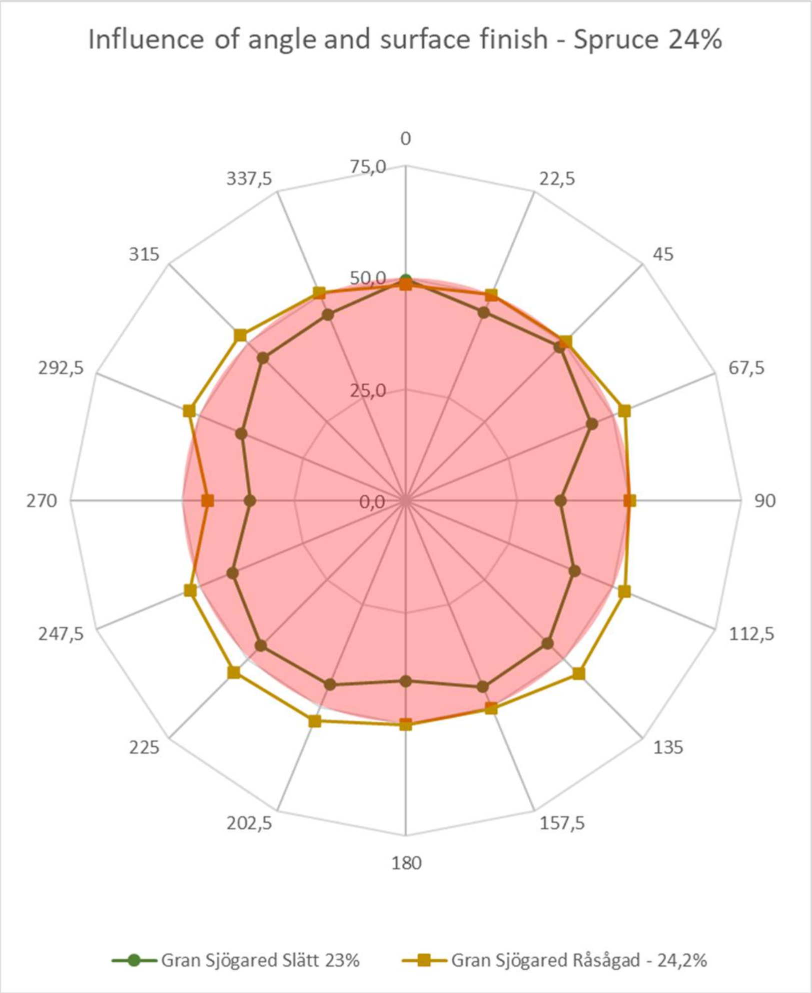


Figure 10: Effect of grain angle and surface texture on SRT result. Finsågad = smooth cut – Råsågad = rough cut.

Existing weathered surfaces outdoors

One thing that is crucial to friction on wood is the presence of biological fouling due to lack of maintenance. Fouling has the potential to degrade the frictional properties of most surfaces, but of wood in particular, by combining with water to build a lubricating film that degrades friction far more than water alone does.

While the evaluation of that effect is not part of this work, we have chosen to measure two wooden substrates in real conditions. The first is a balcony decking painted with a smooth finish. The other is a riverside patio near Lindholmen's Sicence Park on Hisingen, Gothenburg. The reason this surface was chosen was that it was easily accessible, large enough that the work would not obstruct road users and that there were parts of the bridge that were covered by a building overhang, so the impact of that effect could be studied. Both surfaces showed no clear signs of growth, which could mean ongoing maintenance.

Both objects were installed in 2008.

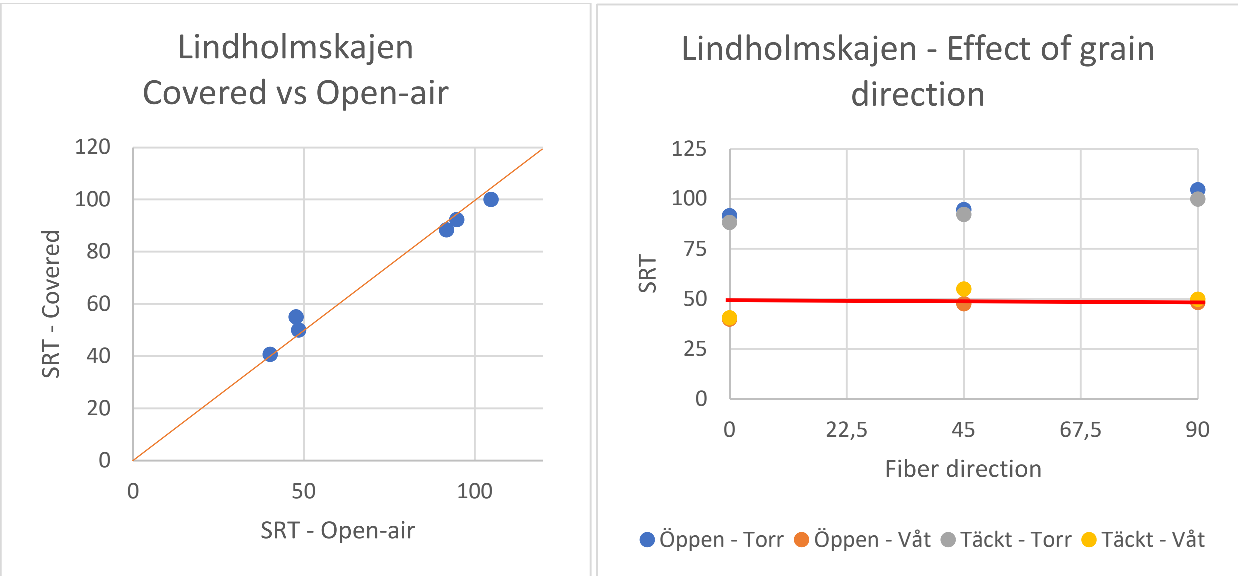


Figure 11: Lindholmskajen's results. Dots above the orange line mean the covered value is higher.

Figure 11 shows that the behavior is different in wet or dry configuration. While the covered part performs better when wet, it gets a lower value dry. This may be because it gets less fouling (and therefore less lubrication), but also wears less which causes a rougher surface texture which can improve friction when the material is dry. However, the differences are small.

On this outdoor run, the method also shows good repeatability.

The results of the measurements on the balcony mainly show that the water content of the boards and the type of surface treatment affect the SRT number more than fiber direction.

Effect of moisture content

Horizontal planks that are exposed outdoors without waterproof surface treatment in our Nordic climate have a moisture ratio on the top surface of between 20 and 40% (own observations) depending on the season, elapsed time since and type of last rainfall, wood species, drying conditions… This can be expected to influence friction through the modification of the surface texture as well as the possible supply of free water to lubricate or, for dry wood, absorbing water preventing the formation of a water film.

Therefore, we have looked at that aspect for two products. First the same plank of untreated spruce and then an impregnated plank, NTR AB brown with a grooved surface (inverted half-circles).

For spruce, we see that the best friction (average of all directions) occurs at 12% moisture ratio while the worst occurs at 32%. The data is too limited to draw firm conclusions but the trend is clear and should be taken into account when designing wooden road surfaces.

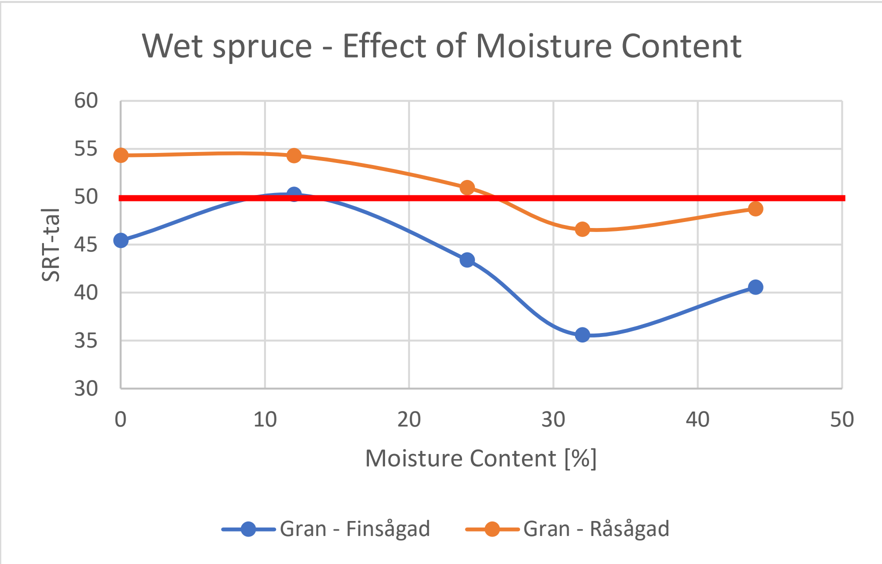
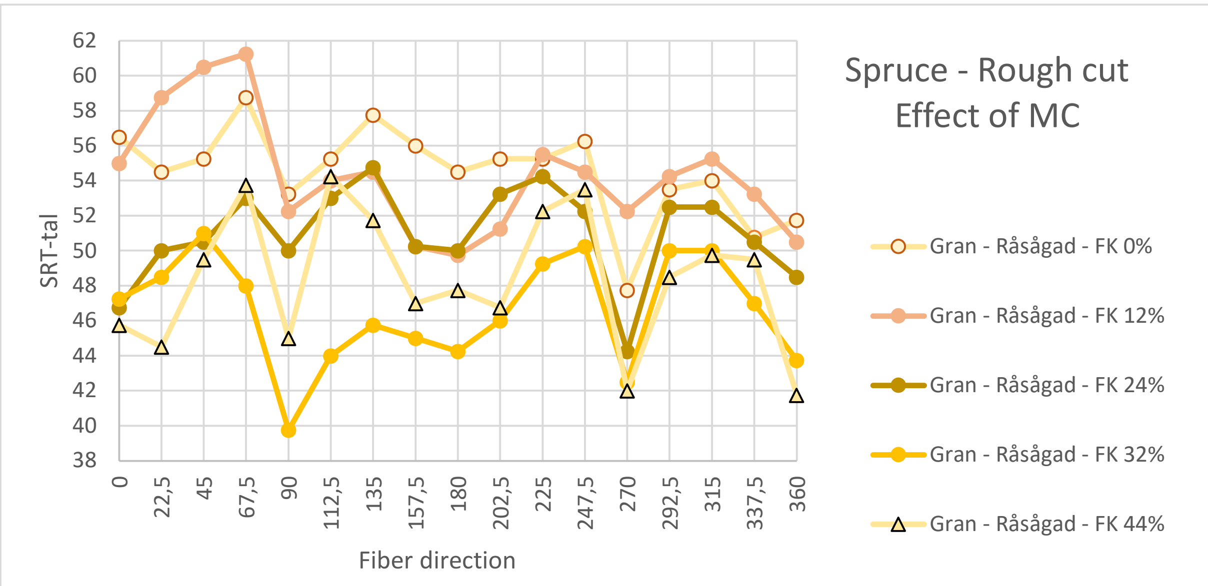
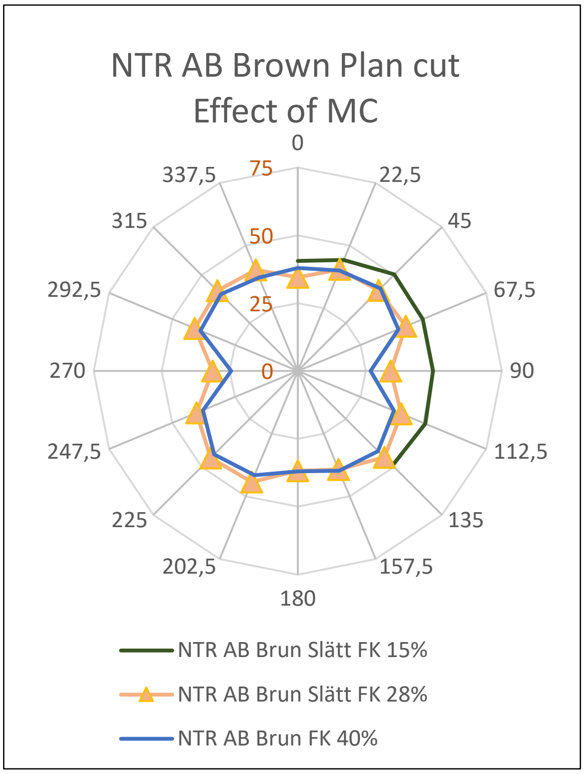
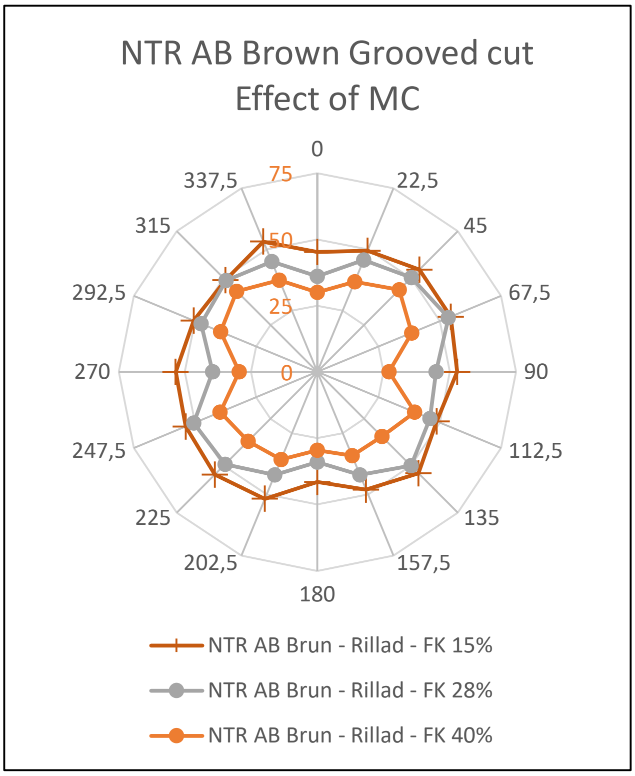


Figure 12: Average SRT number for the same spruce plank depending on moisture content and type of cut



As for pressure-impregnated pine, we have only been able to perform three tests per side, with 15%, 28% and 40% moisture ratio. The results also show that high moisture contents significantly lower friction.





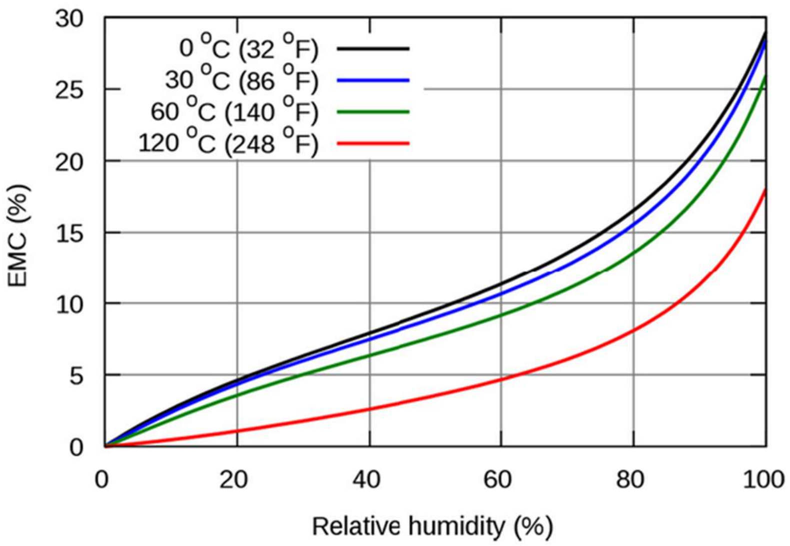
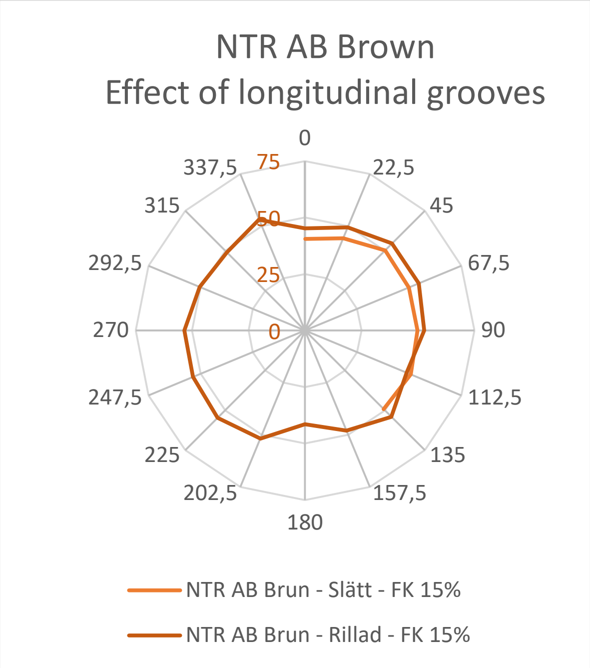


Figure 13: Equilibrium Moisture Content (EMC) for wood in contact with air at different relative humidity[2]

[2] https://www.core77.com/posts/25000/wood-movement-why-does-wood-move-25000

Effect of longitudinal grooves



One of the planks was made of pressure-impregnated pine (NTR AB Brown), probably planed, with a grooved side (see Illustration of the measuring surface on a plank 145 mm wide. Rounded corners and tolerances mean in practice that 45 and 67.5 degree angles often lack a small contact area in the corner. The fibre direction is illustrated by the arrows.

Figure 5).

Many such products are sold with the argument that the grooves improve friction and prevent the risk of falling, mainly for pedestrians and when wet.

To test this, we have carried out measurements of the grooved surface.

There are strong limitations when measuring such a rough surface macrostructure with SRT, and Trafikverket has therefore prohibited the use of SRT for road markings with a macrotextured surface. It is likely that measured values for angles of 90 and 270 degrees are not representative for cyclists as the parallelism between the contact line and the grooves creates unrepresentative dynamic behaviours. In addition, in theory, the rubber pattern of the tire or shoe sole can amplify the effect of the groove (obstruction effect) and therefore lead to a much better improvement of friction in difficult conditions than is shown with SRT. However, exploring this is not part of this work and the effect will vary wildly according to type of tire, inflating pressure, water film thickness and groove profile.

The results below show that the grooving has different effects depending on the moisture ratio and that the effect at 90/270 degrees is not particularly good. The reason may be that the contact area decreases or it may be connected to the selected profile which is rounded and therefore does not add much resistance. The profile is used for patios where people often stay barefoot where it might be an interesting effect, while its added value to cyclists seems to be at best marginal.

It is likely that other grooved profiles may lead to completely different results, and assumptions are that 3D modeling with FEM may be the best way to evaluate this for a real interaction as SRT is too limited for the measurement of coarse and periodic macrostructure, especially when interacting with a complex visco-elastic rubber material.

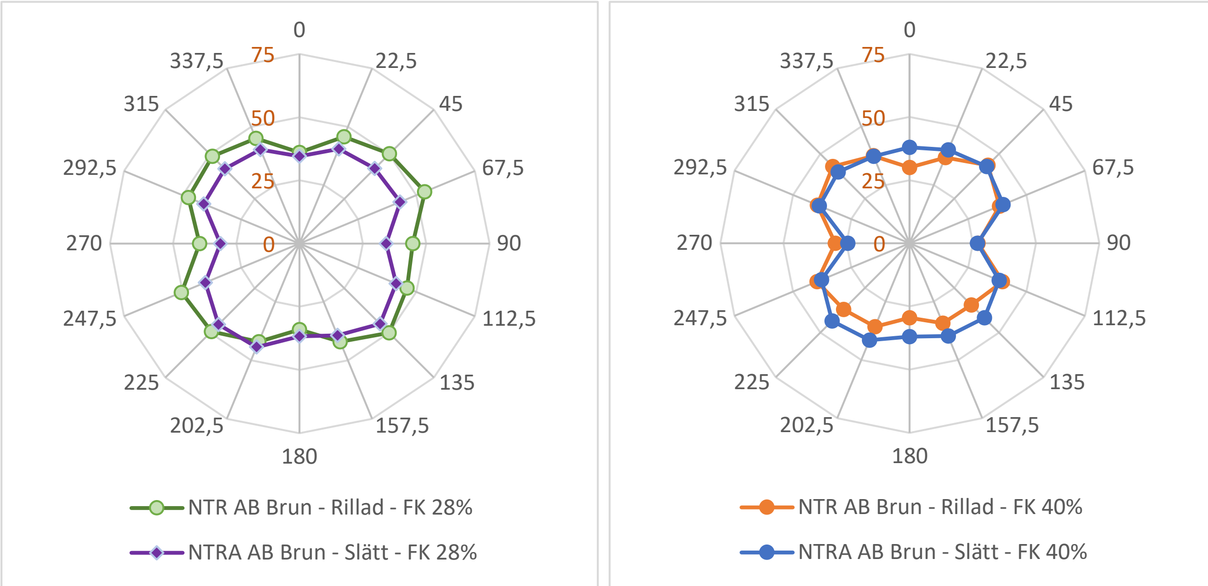
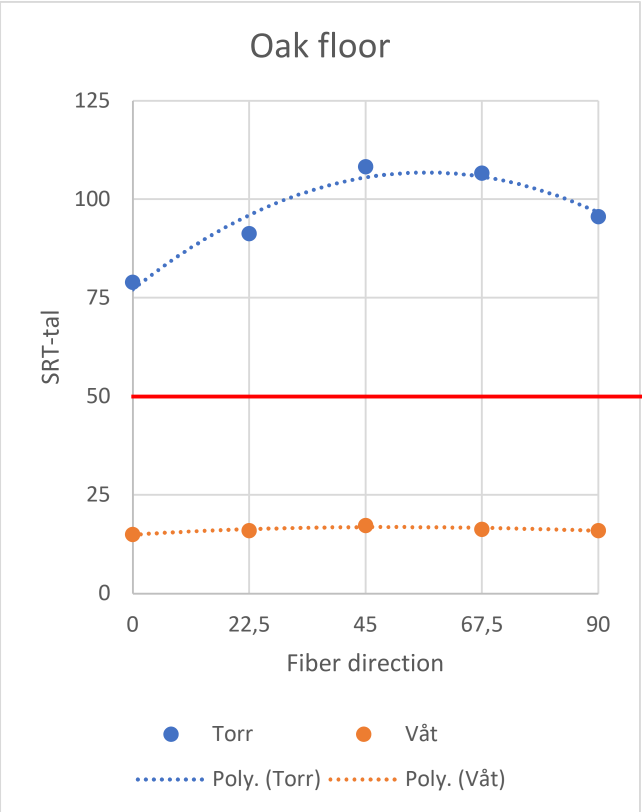


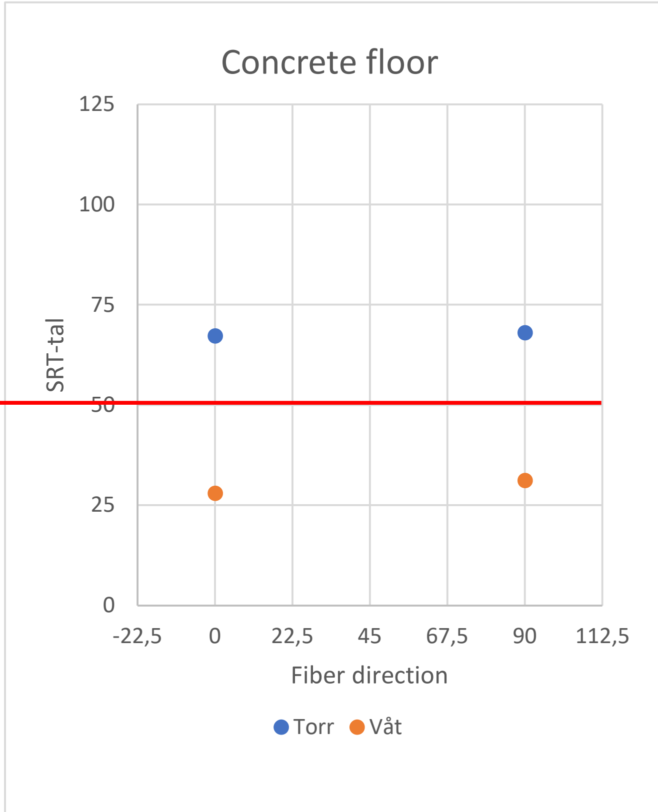
Figure 1: Effect of grooving (rillad) vs smooth cut (Slätt)

Benchmark objects

In order to give perspective to the measurements of the wooden substrates, we have carried out some measurements of common substrates. The results are reported below.

- Stratified flooring in varnished oak
  Common varnished oak flooring (installed 2008) has been measured. The results confirm that such surfaces provide very low friction when wet.
  Note: this is very similar to flooring used in velodrome for cycling speed records.
- Smooth concrete floor (2008)
  A typical smooth concrete floor from the local basement has been measured and demonstrate similarly low SRT numbers.





Test with a 3D-printed calibrating disc

To make the work of measuring friction on wood in different directions more efficient and accurate, we have developed a disc with 32 holes at regular intervals (angles of Π/16). The disc can easily be placed on a jig and rotated to measure at the desire angle without further adjustments.

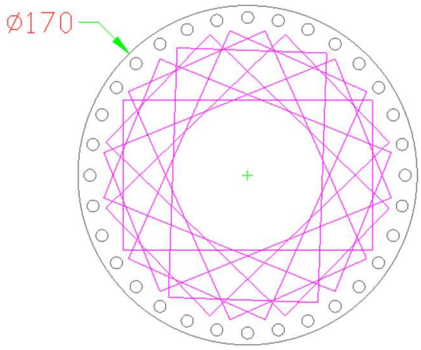
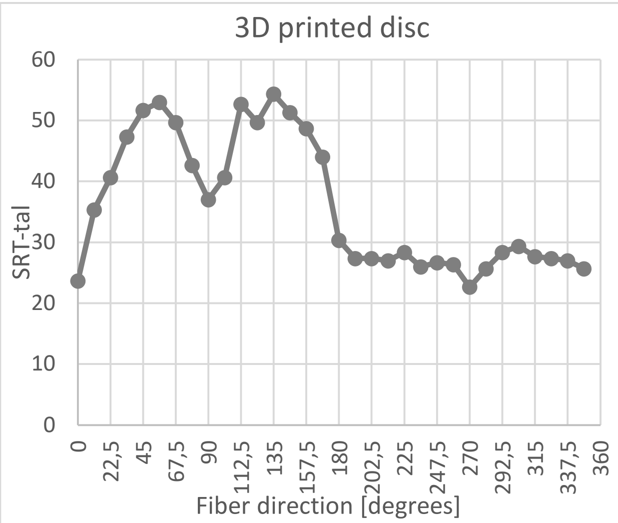


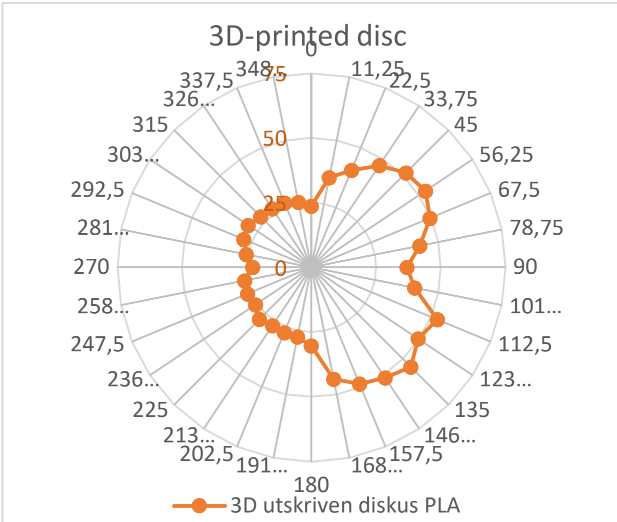
Figure 14: 3D-printed disc in grey with measuring contact patches for half of the angles in magenta.

A wood sample to be measured can then be attached to the board and thus measured with greater accuracy and repeatability.

We have 3D printed a test disk of the proposed type. Since 3D-printing with PLA gives a corrugated surface structure to the disc, we hoped to be able to see a theoretical pattern for fibre direction dependence of the SRT number. As the graph below shows, this is the case for the first half of the measurements. However, the surface structure wears away afterwards and the angle effect disappears for the second half, with the exception of the 270 degree angle where the rubber plate is parallel to the "fiber direction".

Over the first half we see a clear M-shaped curve where friction is lowest at 0 and 180 degrees (fiber direction) and 90 degrees (transverse) and highest between 45 and 60 degrees from the fiber direction. Follow-up measurements on a more permanent substrate have the potential to provide a more complete picture of the effect.





5. Conclusions

We have developed a new method to measure perpendicular to the direction of travel. While the method has proven to be too dangerous to use extensively and to currently provide low quality data only, it has demonstrated the good lateral friction properties of bicycle tires, and the complex dynamic relationships between the system's various parameters that govern effective friction and make it hermetic to reliable measurement, particularly in a cycling context.

The project's biggest ambition was to measure different wood substrates under different grain directions to start generating friction data that would become publicly available. Therefore, all measured values are reported in the appendix, as well as in the form of an excel file on our website.

The measurements were made using the well-established method Skid Resistance Tester (SRT) and a number of interesting tendencies have been identified:

- Friction on wooden substrates is strongly dependant on the angle between the frictional force and the fibers (grain)
- Many parameters contribute to the variation of the friction coefficient and some can have a stronger effect than the fiber direction (water film, contaminated surface or fouling, surface texture, surface treatment)
- Somewhat surprisingly, friction was highest at angles of about 45 degrees to the direction of the frictional force. This could be related to the method used (rectangular pad) or might indicate some interesting design possibilities.
- The wood's moisture content seems to have a decisive effect on the friction coefficient between 15% and 40% MC.
- The grooved surface measured shows a complex influence of the groove on the coefficient of friction. It is uncertain whether the solution leads to a reliable improvement in the frictional properties of the surface, in particular in a cycling perspective.
- To get away from the limitations of SRT, in particular the linear contact surface, it would be possible to combine limited datasets with FEM modelling to be able to get the most out of the data and overcome the difficulty of reproducing a bicycle tire's complex contact surface with the pavement.

In summary, we show that wood has the potential to meet the Swedish Road Administration's requirements for a friction coefficient above 50, provided that the design is done correctly in terms of choice of species, surface structure, surface treatment and placement.

We recommend that planks and boards that will be built into boardwalks and wooden surfaces for pedestrian and bicycle traffic are measured with SRT under controlled conditions to provide road engineers with enough information to design such infrastructure in the safest possible way.

6. Litterature

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Appendix A – Measurement data SRT-tal

Tabell A.1	Dry			Wet		
Fiber direction	0	45	90	0	45	90
Lindholmskajen – Open-air	91.7	94.7	104.7	40.0	47.7	48.3
Lindholmskajen - Covered	88.3	92.3	100.0	40.7	55.0	50.0
Rubber pad	97.0			58.2		
Plywood 2	116.0	97.8	98.0	32.8	32.0	27.8
Thin Oak	101.0	101.4	101.4	56.6	59.8	62.0
Teak	95.6	101.4	98.4	61.6	62.8	59.6
Beech	102.2	106.0	105.4	61.8	66.0	63.8
Humid Plywood	105.0	95.2	98.6	25.8	33.6	32.8
Concrete	67.2		68.0	28.0		31.2
Teak	90.0	100.3	117.7	43.0	54.0	49.3
Larch	110.3		102.0	50.0		45.0
NTRA AB Green	107.3		98.3	51.3		53.3
Spruce untreated smooth cut	95.7	102.3	82.7	59.0	60.3	60.7
Spruce untreated rough cut			114.7	60.3	56.0	54.0
NTR AB Brown grooved	82.0	89.3	103.3	45.0	57.3	52.3
NTR AB Brown smooth	105.7	108.7	114.3	47.3	53.0	46.7

The value is the average of all measurements taken for each set-up (between 3 and 5).

Missing value have not been measured.

0/180/360 degrees mean that the rubber plate moves along the fibers.

Table A.2 presents data for finely sawn spruce boards or raw sawn surface structure.

F or MC stands for Moisture quotient in percent.

Tabell A.2	SRT number for different angle directions [degrees]																		
Spruce Sjögared	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	360	Avg	MC [%]
Fine cut MC0%	45.5	45.5	53.0	47.0	37.5	48.3	49.0	47.8	45.8	46.3	46.5	43.8	36.0	42.5	46.0	46.3	46.3	*45.5*	*0*
Fine cut MC14%	45.8	49.5	53.3	53.5	49.3													*50.3*	*12*
Fine cut MC24%	49.5	45.8	48.8	45.0	34.5	40.8	45.0	45.0	40.3	44.5	45.8	42.0	34.8	39.8	45.3	45.3	46.3	*43.4*	*24*
Fine cut MC32%	36.3	38.5	38.8	33.3	25.3	33.5	39.8	40.3	40.3	39.3	39.5	34.3	24.5	31.0	36.8	39.8	34.3	*35.6*	*32*
Fine cut MC44%	44.0	44.3	45.0	39.0	28.8	38.5	44.8	44.5	40.0	42.8	43.5	39.5	26.5	37.5	44.0	42.5	44.5	*40.6*	*44*
Rough cut MC0%	56.5	54.5	55.3	58.8	53.3	55.3	55.3	56.0	54.5	55.3	55.3	57.7	47.8	53.5	54.0	50.8	51.8	*54.4*	*0*
Rough cut MC14%	55.0	58.8	60.5	61.3	52.3	54.0	54.5	50.3	49.8	51.3	55.5	54.5	52.3	54.3	55.3	53.3	50.5	*54.3*	*12*
Rough cut MC24%	46.8	50.0	50.5	53.0	50.0	53.0	54.8	50.3	50.0	53.3	54.3	52.3	44.3	52.5	52.5	50.5	48.5	*51.0*	*24*
Rough cut MC34%	47.3	48.5	51.0	48.0	39.8	44.0	45.8	45.0	44.3	46.0	49.3	50.3	42.5	50.0	50.0	47.0	43.8	*46.6*	*32*
Rough cut MC44%	45.8	44.5	49.5	53.8	45.0	54.3	51.8	52.3	47.8	46.8	52.3	53.5	42.0	48.5	49.8	49.5	41.8	*48.7*	*44*
NTR AB brown	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	360	*Avg*	MC [%]
Fine cut MC14%	40.5	44.3	50.3	49.8	49.8	50.8	49.3											*47.8*	*12*
Fine cut MC28%	27.0	40.5	42.0	43.0	34.3	41.3	45.0	45.3	36.8	44.3	45.3	40.3	31.3	41.0	41.8	40.3	34.5	*39.6*	*28*
Fine cut MC40%	38.0	40.0	43.0	40.0	26.8	38.3	41.8	43.5	37.0	41.5	43.5	37.8	24.5	38.8	40.0	37.3	36.5	*38.1*	*40*
Grooved cut MC14% #1	45.3	49.5	54.5	54.5	52.8	48.8	54.0	54.8	41.5	51.8	54.8	53.8	53.5	50.5	49.0	53.3	50.5	*51.3*	*12*
Grooved cut MC14% #2	45.0	47.0	53.0	57.0	51.8	54.0	52.8	51.0	42.5	49.3	51.0	51.0	45.8	51.3	47.3	45.8	39.3	*49.1*	*12*
Grooved cut MC28	36.0	45.8	50.3	53.5	44.8	46.0	50.0	49.3	34.0	42.0	49.3	50.5	39.5	47.5	48.8	45.0	36.8	*45.2*	*28*
Grooved cut MC40%	30.0	36.8	43.8	38.5	27.0	39.8	34.5	37.0	29.5	35.8	37.0	39.8	29.5	39.5	43.0	37.5	31.5	*35.9*	*40*
Varnished oak flooring	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	360		
Dry	79.0	91.3	108.3	106.7	95.7														
Wet	15.0	16.0	17.3	16.3	16.0														