Friction as a Measure of Slippery Road Surfaces

Taisto Haavasoja[1] **and Yrjö Pilli-Sihvola**[2]

[1]*Teconer Oy, Helsinki, Finland*
E-mail: name.surname@teconer.fi

[2]*Finnish Road Administration, Kouvola, Finland*
E-mail: name.surname@ely-keskus.fi

ABSTRACT

The meaning of friction coefficient as a measure of a slippery road surface due to the presence of ice, snow or hoar frost is discussed. Practical means of measuring friction on highways are briefly reviewed and compared with a discussion of advantages and limitations. A new simple and inexpensive cell phone based tool to measure friction is presented together with data from various slippery situations.

INTRODUCTION

Friction coefficient is a well defined and unique quantity to describe grip of car tires to road surface. Loss of adequate grip will have dramatic consequences for maneuverability and stopping distance. A thin layer of ice, which may have developed on road surface either by freezing, precipitation or condensing, can reduce friction coefficient easily by a factor of three to four causing the braking distance to increase by the same factor. It is one of the main tasks of winter maintenance to avoid situations developing to slippery surfaces.

Spreading of deicing chemical prior to freezing is a widely proven method to keep friction coefficient high enough for safe driving. Practical measurements of friction coefficient reveal that if deicing chemicals have been applied in due time, a fair part of the solution may still freeze, but in this case the freezing does not cause a dramatic reduction of friction. There is a simple reason for this behavior. When a solution of water and deicing chemical freezes, the forming ice is mechanically softer than clean ice. A physical reason for this kind of soft ice with deicing solutions comes from the fact that ice develops by extracting deicing chemicals out of the forming ice crystals. Thus the frozen surface contains a fair part of concentrated liquid solution in between the ice crystals making the whole structure apparently softer compared to the case of freezing of clean water.

There are some radical consequences from the softness of frozen deiced surfaces. Firstly, friction coefficient may stay at a much higher level compared to the case without any deicing chemicals. In practice, the actual needed amount of deicing chemical is much less than what a formal calculation of required concentration shows, if the calculation is based solely on the phase diagram of the solution. This is a great advantage, since a useful amount of salt can often stay fairly low. For example, a few grams of NaCl per one square meter near 0 °C may be enough to prevent slippery surfaces during a small snow fall, whereas the required amount of salt to prevent any freezing can be many fold.

In terms of numbers, let us say we have surface temperature at -2 °C and we expect a snow fall of 1 cm, which corresponds to about 1 mm of water. Then we would need over 30 g/m^2 to keep the surface fully unfrozen during the snow fall. In reality, to keep the surface friction at a fairly high level, only a few grams per square meter is needed for one 1 cm of snow. A relatively small amount of salt prevents ice forming a solid layer on the surface. The remaining small amount of slush does not reduce friction appreciably, since it will remain soft, and will finally be driven out of the wheel track.

On the other hand, although we may be well off to handle the surface with a small amount of salt, there is still a severe risk that this same case becomes later slippery. If surface temperature is reducing by a few degrees further, the percentage of ice in the remaining solution will increase and finally reach a value, where tire pressure is not anymore high enough to break the ice causing a slippery surface. If the reduction of temperature is not imminent, then it would not help to over salt initially, because the excess salt will be driven away by a fairly slight traffic.

To prevent refreezing of a salty surface it is important to follow the actual friction coefficient on the surface. Since the friction coefficient will reduce slowly with lowering temperature, or with lowering concentration of deicer at a given temperature, there is often enough time to resalt the surfaces, if we just follow the development of friction coefficient frequently. It turns out also that the actual amount of ice can be much higher with soft ice than with hard ice and still the friction is better. Usage of deicing chemicals to prevent slippery surfaces can be optimized by letting surface to partially freeze but still keep friction high. This is done often unintentionally by assuming that the surfaces are just moist or wet without any ice due to the chemicals. Nevertheless, it is essential to know the development of surface friction in these cases to prevent slippery surfaces due to increasing ice amount with dropping surface temperatures causing finally a slippery surface.

Nowadays, there are a couple of means to follow the development of friction coefficient even operationally. In the following we will review a few of them with an emphasis on the operational usefulness. First we will introduce friction coefficient itself as a physical measure.

FRICTION COEFFICIENT

Friction coefficient can be defined for our purposes as the ratio of the vertical force caused by car tire perpendicular to the road surface and the horizontal force due to acceleration or braking of the car so that the tire is close to slipping or lock braking. We should take into account tilting of the road surface, but that is not necessary for ordinary roads with low degree of tilting. A more thorough definition would also consider friction as a function of percentage of slipping. For details look, e.g., at Olsson et.al [1]. In our case we assume that the friction coefficient is determined as the friction force near 20 % slip where the friction is at maximum. Although friction can reduce somewhat with 100 % slip as compared to the maximum value of friction vs. slip as shown in Ref. [1], we use this definition for friction, since most contemporary cars are equipped with an anti-lock braking system (ABS) preventing total slip.

By definition and the above assumptions we get the friction μ with the notation of Fig. 1 as

$$\mu = F_\mu / F .$$

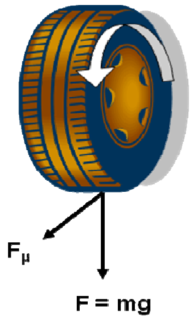

Fig. 1. Friction force F_μ and the normal force F = mg, where m is the mass supported by the wheel and g is the acceleration of gravity g = 9.81 m/s².

Friction force will induce an acceleration a of the mass m supported by the tire, thus we have F_μ = ma. Since the gravity will induce a normal force F = mg, where g = 9.81 m/s², we finally can conclude that

$$\mu = a / g .$$

This equation tells us that (1) friction should not depend on the mass of the car and (2) friction can be measured directly by measuring the acceleration while braking or speeding up so that tires slip or get at least near to slipping. If not all the mass of the car is supported by braking or speeding wheels the above equation needs to be adjusted accordingly. We can also see that friction is an absolute quantity although it does not have units of measure. Consequently, for our purposes there is no need to scale friction in any way and it will remain a unique number for a given case. Friction coefficient represent the maximum attainable acceleration, excluding collision, in fractions of acceleration of gravity and is a very good measure of slipperiness.

This result is subject to our assumptions. Not all tires are the same nor pavement surfaces. Nevertheless, typical friction coefficients of a rubber tire on a dry asphalt surface are about 0.80 ± 0.10 and reduction of friction down to 0.20 level with hard ice can happen even with studded tires. Also, we assumed there should be no other forces than the friction force to affect on the car while braking. One of those other forces could be air or wind drag, but they cause a tolerable effect at low car speeds less than 100 km/h or wind speeds less than 20 m/s. Thus we can conclude that we can rely on measuring acceleration or deceleration while speeding up or braking hard enough to obtain operational friction coefficients of slippery surfaces in winter conditions.

There is also another interesting result in close proximity to the equation of friction and acceleration. If our car is running at an initial speed v_i, then the kinetic energy of the car is $E_k = m\, v_i^2 / 2$. This energy can be consumed by lock braking. Thus the kinetic energy must equal to the work done by the friction force in this case and we get

$$E_k = F_\mu\, \ell$$

where ℓ is the stopping distance from the initial speed v_i to zero speed while lock braking. This equality gives us

$$\ell = v_i^2 / 2\mu g \qquad \text{or} \qquad \mu = v_i^2 / 2g\ell ,$$

so that we can measure friction coefficient by observing the initial speed and measuring the braking distance.

In Fig. 2 there is shown the braking distance as a function of initial speed with a given coefficient of friction within μ = 0.15 – 0.80. This relation tells us important facts about driving in winter conditions. Let us say we are driving at speed of 100 km/h on a dry road. Then we see that the stopping distance is about 50 m. If there is a thin layer of hard ice on the surface, friction coefficient may reduce close to about 0.20. In this case the stopping distance would increase to about 200 m, which is four times longer than 50 m on a dry road. It would take over 14 seconds to stop the car without collision, which is an astonishingly long time, not easy to believe without an experience.

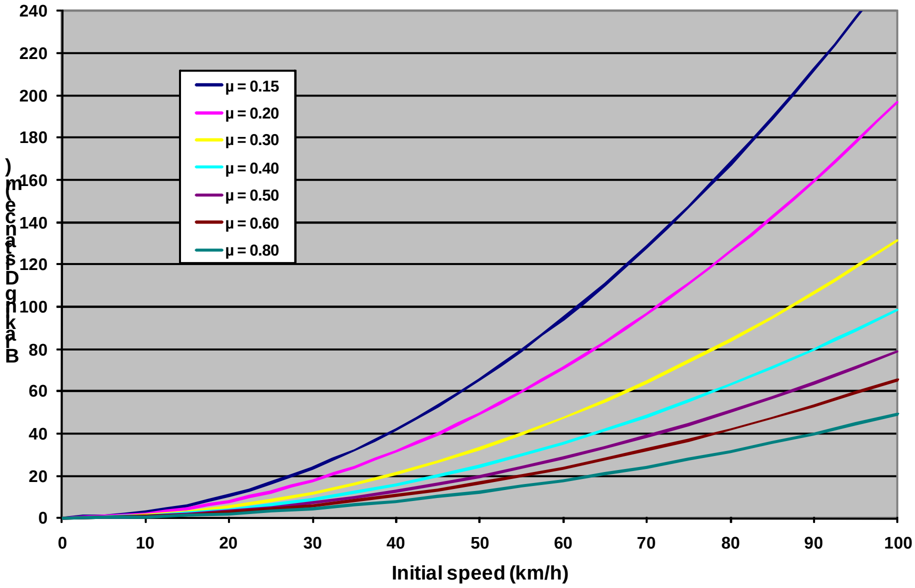

Fig. 2. Braking distance in meters as a function of initial speed in km/h to full stop with a given coefficient of friction μ.

In the above case one could alternatively reduce the driving speed by a factor of two to keep the stopping distance at a tolerable 50 m. Nevertheless, the time to stop the vehicle would still take over 7 seconds compared to 3.6 s on a dry road. Since it is not realistic to keep a 200 m distance between cars, it is more safe and effective to reduce the speed in slippery winter conditions.

PRACTICAL MEANS OF MEASURING FRICTION

Practical means of measuring friction on highways can be divided to methods of (1) measuring mechanical grip force directly, (2) to indirect means measuring amount of water and ice and estimating the hardness of ice by a model or (3) measuring acceleration while braking. There are some other means, like the pendulum friction meter or portable handheld friction meters, but they are not very useful on operated roads. The practical means are reviewed with a discussion of advantages and limitations including a comparison of measured response of two different acceleration based approaches to measure friction.

Friction meters based on measuring force

Most widely used direct force based friction meter is a small trailer on three wheels. Two of the wheels carry the weight of the trailer and the third is the measuring wheel. These wheels are typically chain locked so that the measuring wheel slips and traverses typically 17 % less than the other wheels. The braking force can be measured, e.g., as a chain tension which is easily calibrated to a friction reading. There are many variations of force based friction meters including one wheel versions as reported by Wallman and Åström [2]. Some new force based methods are also reported in Ref. [3].

Force based friction meters are generally considered to produce a reliable friction reading and thus they are good reference instruments. Their main drawback for measuring operational friction in winter traffic is related to their price, size and some need to adapt to the vehicle. It is also important to understand that these friction meters are not absolute, but require a careful calibration at least in the factory if not even in the field use. Special care should be taken to avoid temperature effects in the force measuring mechanics especially in the models using chains.

Friction meters based on indirect measurement

Indirect methods to measure friction are limited to measuring reduction of friction due to ice in one form or another. As discussed earlier in this article hard ice can reduce friction by a factor of four, i.e. the stopping distance is fourfold compared to the case of a dry surface, whereas same amount of soft ice may reduce friction less than by a factor of two, if at all, depending on the deicer content. This fact has been used successfully in the Vaisala Remote Road Surface State Sensor DSC111 to produce friction readings on fully or partially frozen icy surfaces. This sensor can been installed by the road side permanently or on a moving vehicle to report friction by analyzing optically the amount of solution and ice on the surface.

A test to demonstrate the performance of this technique was run with a vehicle containing DSC111 and an accelerometer. Fig. 3 shows the installation of DSC111 on a trailer hook of the vehicle so that the sensor is seeing the right wheel track. The surface states varied from dry to very slippery icy and snowy surface states. In Fig. 4 there are two photographs showing two different roads not far from each other at the same time, one being partially slippery while the other was in normal winter condition with high friction.

Fig. 3. Vaisala Remote Road Surface State Sensor DSC111 installed on a vehicle to measure mobile friction.

Fig. 4. The photographs are taken on the same time from roads near to each other and surface temperature at about -6 °C. There was light snow causing the wheel tracks on the left fairly slippery with friction less than 0.40, while on the right friction was over 0.60. The difference was caused by some more salt on the right. Interestingly, the area between wheel tracks remained practically dry on both roads despite the light snow fall.

The results of the demonstration are presented in Fig. 5. The measured friction refers to the accelerometer reading obtained by occasional lock braking. The DSC111 friction correlates surprisingly well with the accelerometer reading. Only the two lowest measured values are clearly underestimated by DSC111. The reason is that those points corresponded to a very thick layer of ice and packed snow, where DSC111 model tends to assume a low friction. Naturally, with more points on random surface conditions the difference of DSC111 and acceleration readings will increase appreciably. The performance of DSC111 to measure friction is at its best on slippery surfaces with thin layers of ice.

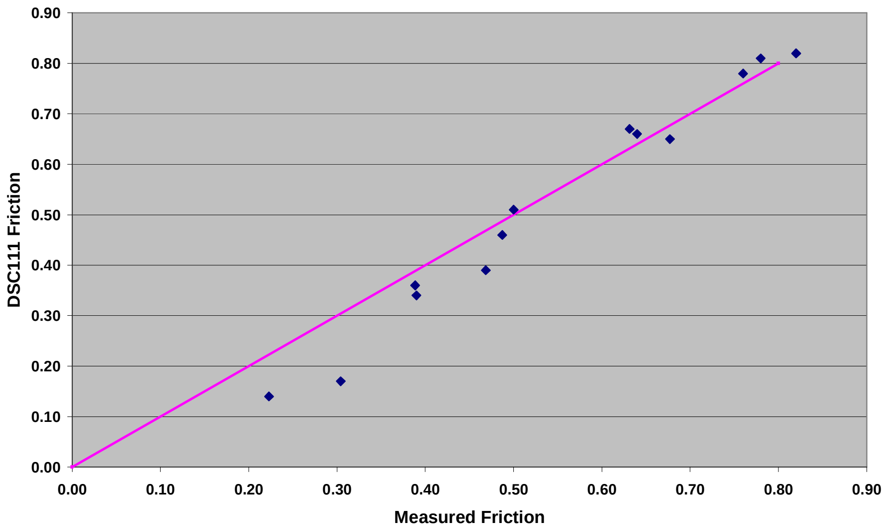

Fig. 5. DSC111 friction versus friction measured by an accelerometer. The red line is only a guide to the eye to show an ideal response. The RMS difference of all the points is on the order of 0.05 units of friction.

Vaisala Remote Road Surface State Sensor DSC111 was also tested by Finnish Road Administration and the results were reported in 15th World Congress on ITS 2008 [6]. The results of the study suggest that the optical sensors provide valuable additional road condition information that cannot be acquired through other monitoring methods. Comparison study 2008 also showed that there are still a lot of differences between the friction values given by the measuring devices which operate using different measuring methods. The friction varies considerably on the road surface across the road and also along the road. So it is very difficult to define that "right" friction value exactly.

There are also many other indirect means to observe friction including those based on electronic stability control (ESC) or on some additional equipment installed in a vehicle. Ref. [3] lists some of those and describes some recent development in detail. We shall not repeat those means here, but instead we just want to remind generally that indirect means to measure friction have not yet been applied widely presumably due to cost or prototyping level of maturity.

Friction meters based on acceleration

Acceleration has been applied for measuring friction on roads for long. Some of the early equipment were based on measuring forces on a macroscopic piece of mass. Nowadays they have been replaced by meters exploiting micro-electro-mechanical sensors, which can provide acceleration digitally and often all three axis. There are still in use friction meters which observe a change in speed while braking and calculate acceleration by dividing the change in speed by time of braking. An example of that kind of sensor is Eltrip-45nk, look at Ref. [4]. These sensors seem to suffer from accuracy due to difficulty to determine the effective time of braking. The reported values tend to be too low. In one test run the reading was over one third smaller than actual acceleration.

The latest innovation measuring friction employs modern cell phones, most of which have a build-in acceleration sensor. To measure friction by a cell phone one needs only to install an application program to the cell phone. The acceleration sensor must be calibrated, but that is straightforward by the help of acceleration of gravity. The left side of Fig. 6 shows the display of an application called µTec and produced by Iriba Oy [5].

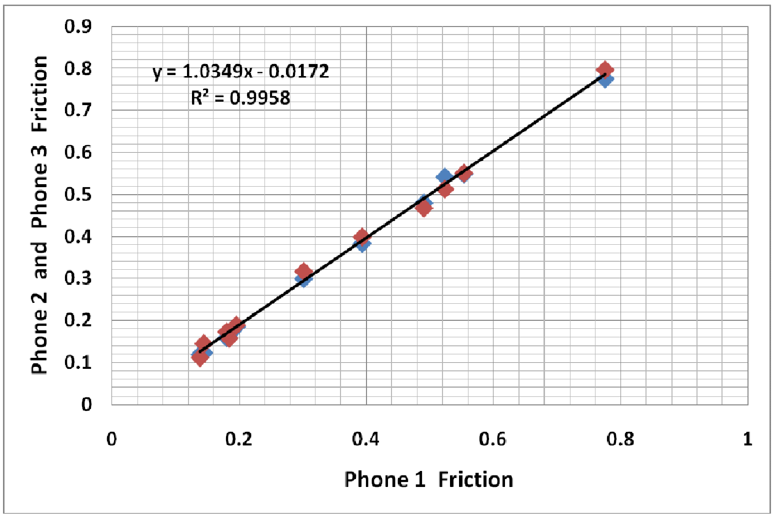

Fig. 6. On the left side a cell phone based friction meter called µTEC of Iriba Oy. The display shows the last measured acceleration value during braking or speeding up. The data is also available to other users through a server by a Mobile Friction Measurement Service. On the right side a comparison of three cell phones to braking. The phones were installed in the same vehicle and the points were recorded as maximum acceleration in the driving direction.

On the right side of Fig. 6 there is a comparison of three different cell phones measuring acceleration while installed in the same vehicle. The vehicle was braked intentionally for a fairly short time, typically a fraction of a second. As can be seen a cell phone can be used as an accurate accelerometer and applied for measuring friction. Measuring friction by speeding up has the advantage of requiring less acceleration than braking with a two wheel drive vehicle and it is also safer to accelerate than to decelerate in dense traffic.

CONCLUSION

We have discussed the importance of friction as a measure of slippery road surface state in winter conditions, peculiarity of freezing of deicer solutions, and consequently, the reason why amount of ice does not always correlate with friction. The strategy of salting or deicing must rely on small amounts and adding later more if needed, since excessive presalting may be lost due to traffic by the side of the road. Thus following development of friction is necessary to avoid accidental refreezing. Although there are numerous ways of measuring friction on roads the operational methods must have properties like easily installed and used, economic and reliable result. Acceleration based friction meters embody most potential in this respect.

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