The Measurement and Theory of Tire Friction on Contaminated Surfaces

JAMES C. WAMBOLD AND ARILD ANDRESEN

In the past five years there has been an International Experiment to Harmonize Friction Measurement by the World Road Association (PIARC) and within the past three years there have been at least four separate studies on winter friction, a five year joint winter runway program between NASA, FAA, Transport Canada (TC), the Canadian National Research Council (NRC), the Norwegian Civil Aviation (NCAA) and the French Civil Aviation Administration; a study by the Norwegian Road Administration with Norsemeter; a study by Minnesota DOT and the Concept Highway Maintenance Vehicle Study by the Iowa Center for Transportation. In addition to these studies there are standards under development: an International Friction Index (for wet pavements) and an International Runway Friction Index (for winter operation). This paper summarizes the results of these various studies. In the case of wet pavements we now know that the tire first determines the friction slip characteristics until the peak is reached and then beyond the peak the pavement's ability to drain the water determines the speed gradient. When the tire makes contact with the pavement the tire is the sacrificed part of the friction pair; however, on ice and snow the opposite is true and the ice or snow is the sacrificed part of the friction pair. Thus the peak friction that is developed depends on the shear strength of the sacrificed part. With these studies completed, the highway and aviation communities will be better able to measure friction on contaminated pavements.

INTRODUCTION

In search for a better understanding of braking friction processes, mathematical and graphical models that can describe and visualise the processes are useful. Engineered models are usually limited and often inadequate in their capabilities to capture the true, real world processes. We never accept the lesser models that simplify the real world, when they yield plausible results in the area of focus or application.

This paper looks at some existing models for longitudinal friction in the tire-pavement interaction and tries to incorporate parameters of influence found on winter surfaces. The area of interest encompasses all surface types and conditions, which are considered operational for aircraft ground movements. The models are developed in a context of defined surface classifications. Just as pavement friction models reflect the application to pavement as a base surface, we will look at friction models for ice based and snow based surfaces.

J. C. Wambold, CDRM, Inc., 1911 East College Avenue, P.O. Box 1277, State College, Pennsylvania, 16804. A. Andresen, Mobility Friction Technology, Obersl Rodes vei 89b, 1165 Oslo, Norway.

Models Modification Requirements

One possible use of the model modifiers is to adjust an actual measurement to a standard condition with any modifier developed. For example, if a reference is standardized to represent values of friction at -10 degrees Celsius, the actual measurement can be adjusted from the actual temperature during a measurement to the reference temperature using a temperature modifier.

A tire configuration term is used to group the signatures in families per tire configuration. A tire configuration comprises make and type of tire (footprint, rubber compound, longitudinal stiffness), the inflation pressure used and the normal load used during braking operations. The brake actuator control technique is also considered part of the tire-configuration.

Modifications of the pavement friction models are studied as the new parameters and variables are introduced to cater to the sacrificial surface mechanism (hardness/ultimate shear strength), surface temperature, friction enhancing abrasives (sand, grit) and mechanisms such as rolling resistance, fluid planing and fluid drag. Contaminant compression is imbedded in the shear strength term and is considered for inclusion in a rolling resistance term, pending further investigation. These empirical modifications are good starting points for experimental analysis.

GENERAL TIRE-SURFACE FRICTION MODELS FOR PAVEMENT

The following is a brief review of some available tire-surface friction models using ground speed and slip speed as the independent variable. When the models are applied on experimental data, especially those obtained under the Joint Winter Runway Friction Measurement Program, actual tire configurations will be reflected in reference curves for the calibration and harmonisation of friction measurement devices. A single device or combination of several devices (called a virtual device) may be chosen as a Master Device or Prime Calibration Reference Device.

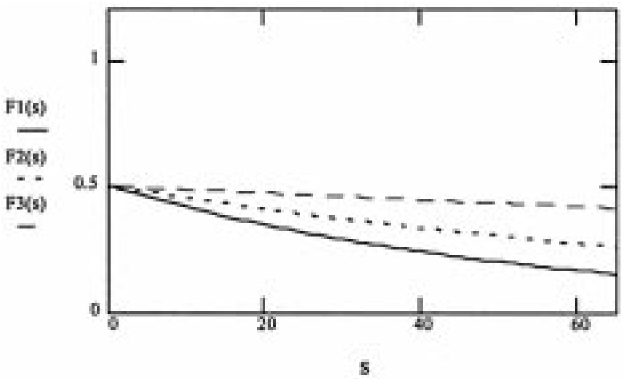

FIGURE 1 Effect of high and low speed constants S_{p1}=55, S_{p2}=100, S_{p3}=340. Lower curve is S_p=55.

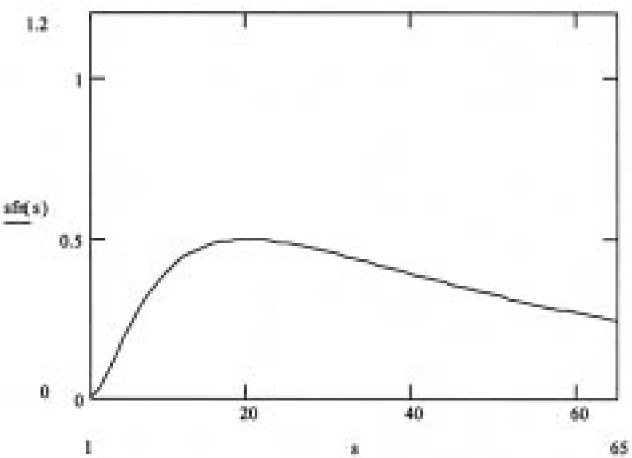

FIGURE 2 A sample friction curve generated with the Rado Model.

The Penn State Model

The Penn State Model is an exponential function with slip speed as independent variable. The model has been used for wet pavements to monitor macrotexture. The model is the basis for the PIARC Model used with the International Friction Index. The model is used here with a zero intercept constant, F_0, and a constant slip speed constant, S_p. Equation (1) is given below and shown graphically in Figure 1 with the following set of parameters:

s = 1 through 65 km/h, F_0 = 0.5, S_p = 55, 100, and 340 with Equation (1).

The speed constant governs the slope of the curve. A higher speed constant makes the curve more flat. The speed constant expresses the influence of macrotexture of the pavement. High macrotexture corresponds with a high speed constant. For the International Friction Index, it is derived from a texture measurement and used with the friction value at the harmonization slip speed of 60 km/h.

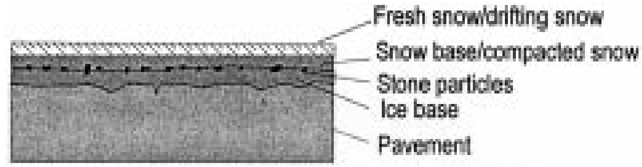

FIGURE 3 A cross section of a winter surface. The pavement can be found with any one or several of the indicated layers. All possibilities of the surface classification are not shown, for instance, wetness.

The Logarithmic Pavement Friction Model

The Logarithmic Pavement Friction Model (also called the Rado Model) is currently used with variable slip friction devices to report three friction variables. The model introduces a logarithmic ratio of slip speed vs. critical slip speed and a shape factor, C (originally designated $\hat{C}$). The critical slip speed (abscissa value), S_c, and peak friction value (ordinate value), P, fixes the location of the maximum friction value on the Cartesian graph of friction vs. slip speed and, therefore, governs the initial climb of the curve. We note that P and S_c fix the position of the maximum friction point.

The set of parameters used in the Rado Model, Equation (2), is s= 1 through 65 km/h, P= 0.5, S_c= 20 km/h, C= 1.4 and is shown in Figure 2.

$$\text{sfn(s)} := P \bullet \exp\left[-\frac{In\left(\frac{s}{S_c}\right)^2}{C^2}\right]$$

Note that the actual resulting curve shape depends on both C and S_c. It has been found that the three Rado Model parameters generally vary with measuring speed. We shall propose speed function for these parameters for winter surfaces in later sections.

COMPOSITE WINTER SURFACES

We introduce the composite surface classification depicted in Figure 3.

The braked wheel can displace all or a large part of a layer of slush, fresh snow or drifting snow that has a fluid powder character. This gives rise to contaminant displacement drag forces on the wheel and varying levels of fluid lift and fluid lubrication as some of the fluid contaminant gets trapped under the tire. Compression may occur with the trapped snow to build a thin layer of new snow base in the track of the wheel. When there is sand applied to the surface (likely before the snow base in Figure 3), it will interact with the tire and raise the friction force experienced. Even in cases without fresh snow/drifting snow, the snow base may be sufficiently soft for the tire to shear off snow crystals during braked wheel rolling and create small amounts of powder to sustain a partial planing condition.

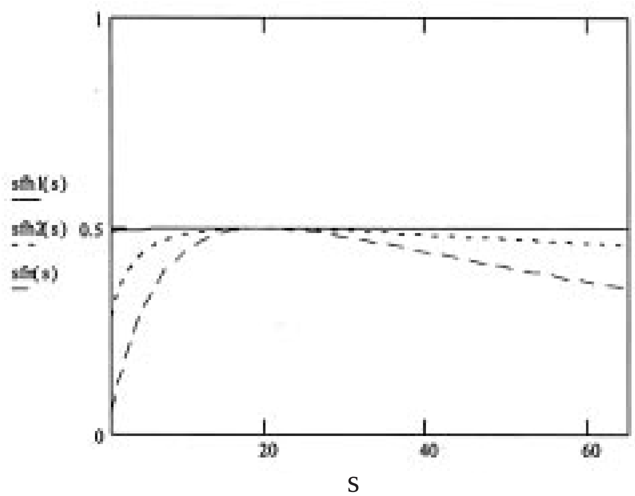

FIGURE 4 A hardness parameter applied to the Rado Model. The upper curve is softest with H=0.1, middle curve is H=0.5 and lowest curve H=1 (hard surface).

Except for clean or damp pavement and clean ice there is always a presence of partial planing. For hydroplaning (liquid water) the fluid dynamic lift part of planing does not contribute significant frictional forces. Only the remaining tire surface contact area is yields braking friction.

For snow planing the shear forces of a laminar or turbulent flow of snow powder at high speeds generates significant shear forces in the planing contact area.

THE MODIFIERS PROPOSED

Surface Shear Strength and Compressive Strength of Snow

For a snow base we need a parameter to express the sacrifice of the surface, as opposed to the pavement, where the sacrifice part of the friction pair is the tire. The onset of such a sacrifice, shearing off or crunching the snow, occurs when the demand for shear force exceeds the shear strength of the snow. The normal load may crunch the snow at local stress concentration points. Automotive type tires and friction tester tires have stress concentrations along the sidewalls. The crushing occurs when the compressive strength of the contaminant material is exceeded.

In the Rado Model C is related to Sp when 1.7<C<6 for wet pavements. In that range C expresses macrotexture influence for rigid surfaces. For winter contaminants the surface may behave as a hard, non-sacrificial surface, or as a loose, sacrificial surface.

The sacrificial surface should not be expected to show any strong relationship to macrotexture, when the ultimate shear strength has been exceeded and some material has been torn loose. Experiments then show friction forces versus speed as a flat curve even though there is no macrotexture. The interpretation of macrotexture with the Penn State Model is not valid for the sacrificial base surface like snow. The surface shear effect masks the macrotexture.

A parameter to reflect loss of coherence is therefore introduced. In the following, pavement friction models are amended on an empirical basis with a parameter for surface hardness, H. A rigid surface base has a value of H = 1' a soft surface base less than 1. C of the Rado Model is associated with winter-contaminated surface and is interpreted as $\left(\frac{C}{H}\right)^2$. The parameters for Figure 4 are P = 0.5, S_c= 20 km/h, C = 2, H = 0.1 and H = 0.5.

Equation (3):

$$\text{sfh}(s) := P \bullet \exp\left[-\frac{In\left(\frac{s}{S_c}\right)^2}{C^2 \bullet \frac{1}{H^2}}\right]$$

Contaminant Displacement Drag

The equation (Equation [4]) for contaminant displacement drag by the frontal area of the tire is generally:

$$F_{DRAG} = 0.5 \cdot C_D \cdot \rho \cdot A \cdot v^2$$

Since we will be tabulating parameters per surface class and tire configuration, we can simplify the equation (Equation [5])to

$$F_{DRAG} = k_{drag} \cdot v^2$$

Where $k_{drag} = 0.5 \cdot C_D \cdot \rho \cdot A$

The frontal area, A, on the tire is the product of the tire width and fluid contaminant layer thickness.

Surface Temperature

Surface temperature is observed to raise friction level on winter contaminated surfaces as temperature falls. The mechanisms producing that effect are many. A major effect is believed to be a rise in friction due to the increased shear strength and the absence of free water, which could act as a lubricant.

For convenience we choose the Kelvin temperature scale as basis for temperature modelling. That way we do not have to work with a minus sign below freezing temperatures. The temperature adjustments will be done with two linear equations. The number 1 adjustment will be valid from 268 to 273 Kelvin. Number 2 adjustment will be valid below 268 Kelvin. These ranges will be adjusted after investigating the available field-test database.

The composite temperature function is shown in Figure 5.

TABLE 1 Winter Parameters for One Tire Configuration and One Surface Type and Condition

Winter Parameter per Tire Configuration	Designation	Unit	Range	Source
Shapefactor	C	Dimension less	1.4<C<11	Variable slip measurement
Shapefactor Speed Number	c_v	km/h		Variable slip measurement
Loss of Hardness Factor	H	Dimension less	0.05<H<1	Test program table per surface type and condition
Temperature Factor 1	k_{temp1}	Dimension less	$0.001 < k_{temp1} < 0.1$	Test program table per surface type and condition
Temperature Factor 2	k_{temp2}	Dimension less	$0.0001 < k_{temp2} < 0.01$	Test program table per surface type and condition
Planing Factor	k_p	Dimension less	$0 < k_p < 1$	Friction measurement or table from test program
Drag Factor	k_{drag}	sfn/km²/h²	$1 \cdot 10^{-5} < k_{drag} < 3 \cdot 10^{-2}$	Friction measurement or table from test program
Rolling Resistance	R	Dimensionless	0.0001<R<0.3	Friction measurement or table from test program
Abrasive Application	A_a	Dimensionless	$0.01 < A_a < 0.2$	Friction measurement or table from test program
Peak Speed Factor	k_v	km/h	$100 < k_v < 1000$	Test program table per surface type and condition
Ultimate Friction Value	P_0	sfn	$0 < P_0 < 1.2$	Test program table of averages per surface type and condition
Ultimate Critical Slip Value	S_0	km/h	$0 < S_0 < 30$	Test program table of averages per surface type and condition
Critical Slip Ratio Factor	k_c	km/h	$100 < k_c < 1000$	Test program table per surface type and condition

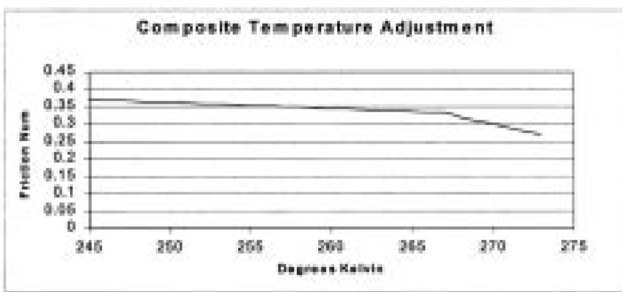

FIGURE 5 Temperature adjustment function consisting of two lines with an intercept at 267 Kelvin.

A temperature dependency term, k_{temp}, is introduced as the gradient of a linear equation, with T being a difference in temperature from a reference.

Rolling Resistance

Rolling resistance has been shown to be a geometrical relationship involving the position, a, of the resultant normal force reaction from ground and the deflected wheel radius, r.

Equation (6):

$$F_{X,R} = \frac{a}{r} \cdot F_{WEIGHT}$$

Compaction Rolling Resistance

For loose snow the tire will compress the loose snow to a higher density, when caught under vertical force, is treated as rolling resistance. The horizontal force is treated as a drag force, F_{XC}.

Equation (7):

$$F_{xc} = k_c \bullet 1/r. \bullet w \bullet d_c \bullet \rho \bullet v$$

Where r is the tire radius, w is the tire width, d_C is the depth of snow layer compacted, ρ is the snow mass density, v is the tire velocity and k_C is a factor of compacting.

For a given tire configuration the r and w are fixed. These parameters can thus be combined into the k_C factor.

Viscous and Dynamic Fluid Lift Planing

The presence of water or water in solutions of de-icer chemicals introduces hydroplaning when the surface is hard and dense enough to support it. Wet, hard ice is an obvious candidate for hydroplaning.

Partial planing may be operational. It can be treated as loss of contact area for solid interaction. As peak friction is very susceptible to the net or real contact area, a planing fraction parameter, $k_{planing}$, for the peak friction value is introduced. The general equation (Equation [8]) for dynamic fluid lift (planing) is

$$F_L = 0.5 \cdot C_L \cdot \rho \cdot A_L \cdot v^2$$

Where C_L is a lift coefficient, ρ is the density of the fluid and A_L is the area of the tire being lifted.

For convenience we use the work by Horne of NASA.

Equation (9):

$F_L = k_{pl}\, v / V_C$

Where k_{pl} is a lift coefficient, V_C is the critical planning speed for the tire-surface and v is the speed this lift gives rise to a horizontal slip friction on the remaining not detached tire-surface contact area. Thus we have Equation (10):

$F_{XL} = \mu_{slip}\, Fweight\, (1 - v/V_C)$

TABLE 2 Penn State Winter Parameters for One Tire Configuration and One Surface Type and Condition

Winter Parameter per Tire Configuration	Designation	Unit	Range	Source
Speed Constant	V_p	km/h	$10<V_p<1000$	Fixed slip measurement
Loss of Hardness Factor	H	Dimensionless	$0.05<H<1$	Test program table per surface type and condition
Temperature Factor 1	k_{temp1}	Dimensionless	$0.001<k_{temp1}<0.1$	Test program table per surface type and condition
Temperature Factor 2	k_{temp2}	Dimensionless	$0.0001<k_{temp2}<0.01$	Test program table per surface type and condition
Planing Factor	k_p	Dimensionless	$0<k_p<1$	Friction measurement or table from test program
Drag Factor	k_{drag}	$sfn/km^2/h^2$	$1\cdot10^{-5}<k_{drag}<3\cdot10^{-2}$	Friction measurement or table from test program
Rolling Resistance	R	Dimensionless	$0.0001<R<0.3$	Friction measurement or table from test program
Abrasive Application	A_a	Dimensionless	$0.01<A_a<0.2$	Friction measurement or table from test program
Ultimate Friction Value	F_0	sn	$0<F_0<1.2$	Test program table of averages per surface type and condition

SUMMARY OF MODIFIERS

The Logarithmic Model

In summary, we have 13 parameters to determine, slip speed, s, travel speed, v, and temperature difference, T, are variables of the process (Table 1).

Penn State Model

The modifiers are designated in the same manner as for the logarithmic friction model. Field-testing will show if they must be treated as two different sets of modifiers or if we, in practice, may use them with both models. The speed constant is unique for the Penn State Model and is meaningless with the logarithmic model.

The modified Penn State Model comprises 9 modifiers (Table 2).

PRELIMINARY RESULTS FOR NORTH BAY TESTS

From the North Bay tests it has been shown that there is no speed effect. Since they are all run at low fixed slip ratios there is not a very good speed range and thus not very good data to determine speed effect. Devices that had variable fixed slip ranges did show speed effects, but not enough data was collected. This coming year a better test plan to explore speed effect will need to be devised. For some devices temperature effects were determined. It should be noted that better temperature measurement will be needed and all devices will need to be equipped with their own surface temperature measurement. Last, preliminary results show that for the conditions of ice and packed snow that:

- All devices participating, a simple correlation is possible if the data is grouped so that only the same conditions, in the pared groups are correlated.
- That contact pressure is a very strong influence, in fact in the simple correlation there is a very strong influence of contact pressure on the multiplier constant (correlation is $R^2=0.82$).

There is more work to do, however, preliminary results show that the various modifiers are playing an important roll and help in developing the test plan.

PRELIMINARY RESULTS FOR MINNDOT AND NORWAY TESTS

This preliminary project was successful in establishing better Bayesian values (filtered peak friction value) and showed that the Rado Model constants can be used to differentiate contaminates. The peak friction along with the slip speed at the peak separates the ice and snow from dry or wet. The shape factor then separates loose snow and slush from packed snow and ice. The project showed that friction levels can be monitored in real time and salting control does appear to be feasible either with a go-no-go or perhaps with varying levels of salting.

More sites where to be tested last season to finalize how the three Rado constants can be used to differentiate the contaminate; however, there was not proper conditions and the tests are to be rescheduled for this coming year. It is planned to continue the study in the US with more experiments. MinnDOT, IowaDot and MichiganDOT mounted a unit on a salting truck and will evaluate its use during the coming winter season.

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