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Tribology Approach to Predict the Variation of Tire/Wet Road Friction with Slip Speed

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ABSTRACT

In this paper, a new model for the speed dependency of friction is developed. The model formulation is based on existing knowledge in tribology, especially in lubricated-friction research. The proposed mathematical formula is found to be a generalization of the well-known PIARC model. Fitting of the new model to experimental data is shown. Attempts are made to related the model constants to measurable parameters such as surface macro- and microtexture, wheel slip, tire tread depth and water thickness.

RÉSUMÉ

Dans cet article, on présente un nouveau modèle de variation du frottement avec la vitesse. La formulation du modèle est basée sur des connaissances existantes acquises dans le domaine de la tribologie, plus précisément dans des recherches sur le frottement en condition lubrifiée. La formule mathématique du modèle représente une généralisation de celle du bien-known modèle AIPCR. L'ajustement du nouveau modèle sur des données expérimentales est montré. Les constantes du modèle sont mises en relation avec des paramètres mesurables comme la macro- et microtexture de la surface de chaussée, le glissement de la roue, la profondeur de sculpture du pneumatique et l'épaisseur du film d'eau sur la chaussée.

1- INTRODUCTION

The friction between a tire and a wet road surface varies with the vehicle speed, due to the mutual influence of water and road surface texture. The knowledge of the speed dependency of friction is important for various applications: estimation of the braking distance, assessment of the pavement skid-resistance, etc.

Numerous models describing the friction – speed curve were developed and validated [1][2][3]. The major drawback is that a given model can not be used to fit any data set, since it was developed for specific test conditions. For non-expert users aiming to analyze their own friction measurements, it is not easy to know which model to employ.

In a paper presented at the 3rd Symposium on Pavement Surface Characteristics [4], the authors mentioned the usefulness of tribology approach, especially the use of the so-called Stribeck curve for tire/road friction purpose. According to these authors, the main advantage of this approach is that all important friction parameters are gathered in the same curve. In another paper dealing with lubricated friction between metal sheets [5], it was found that the Stribeck curve can be used as a master curve to represent the variation of friction with test speed, for various surface roughness.

The Stribeck curve seems then to be a promising tool to describe the tire/road friction – speed curve. Nevertheless, no related work is found up to now in the literature. The objective of this paper is to explore this possibility in developing a model for friction – speed curves based on the Stribeck curve. The relevance of the new model will be validated through its ability to fit measurements performed under various conditions and to explain the apparent divergence between existing models.

2- EXISTING FRICTION – SPEED MODELS

The usual scheme of the tire/wet road contact area is illustrated in the figure 1. The assumed and well accepted contact conditions are the following:

- In zone 1 in front of the contact area, the water film tends to lift the tire;
- In zone 2, the tire is supported partly by the water film and the road surface asperities;
- In zone 3, full contact is developed. It is not clear if whether fully dry condition is reestablished or there is still a very thin water layer at the tire/road interface.

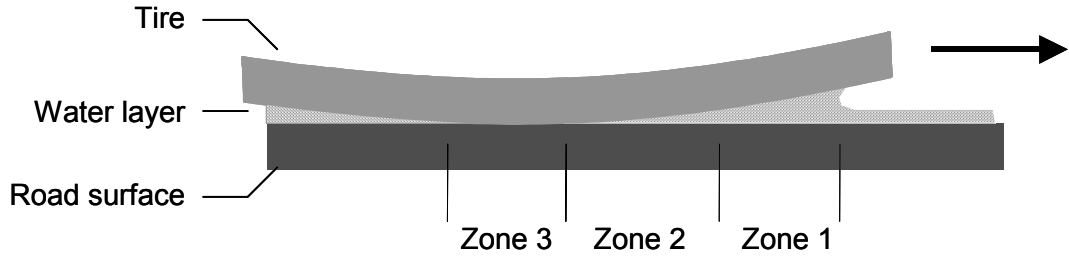


Figure 1. Scheme of tire/wet road contact area

Based on this scheme, tire/wet road friction is mostly developed in zone 3 and the variation of friction with speed depends on the ratio between zone 3 and the total contact area, meaning that:

$$\mu = \mu_{\text{dry}} \frac{A_3}{A_1 + A_2 + A_3} = \mu_{\text{dry}} \left(1 - \frac{A_1 + A_2}{A_1 + A_2 + A_3} \right) \quad (1)$$

Where

- μ : coefficient of friction;
- μ_{dry} : coefficient of friction generated in zone 3;
- A_i ($i = 1, \dots, 3$) : areas of zone “i”.

The above formulation can be rewritten as:

$$\mu = (\text{adhesion term})(1 - \text{hydrodynamic term}) \quad (2)$$

Actually, the friction developed in zone 3 is often referred to as “adhesion friction”, and the sum of zones 1 and 2 is related to water penetration. All existing friction models are based on this general scheme.

In the figure 2, two examples of friction – speed variation are shown. The graph shapes are typical of what can be found in the literature:

- Exponential or almost linear (Fig. 2a);
- Inverse-S (Fig. 2b).

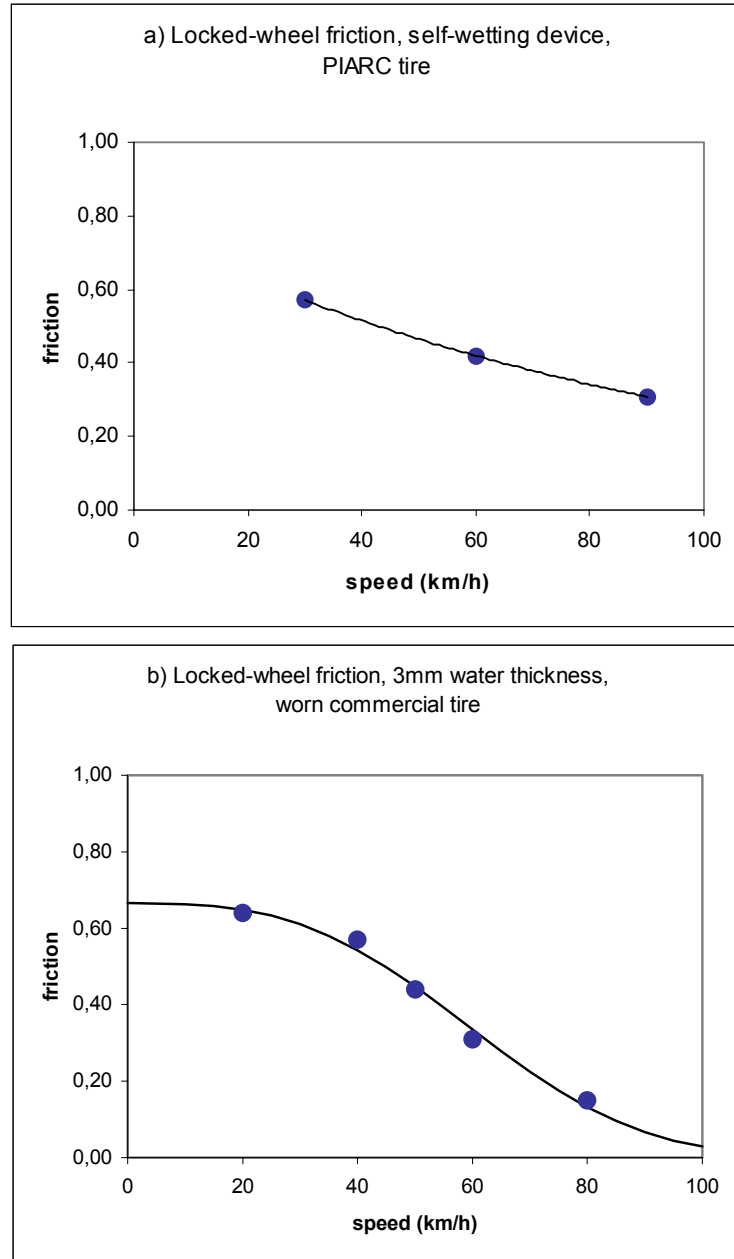


Figure 2. Typical friction – speed variations
(Data source: BRRC (Fig. 2a) and CETE Lyon (Fig. 2b))

Dijks [1] proposed the following formula for the linear shape:

$$\mu = a_1 + a_2 \frac{V}{TD} + a_3 V + a_4 BPN + a_5 V \cdot BPN + a_6 \frac{V}{TD} \cdot BPN \quad (3)$$

Where

- μ : coefficient of friction;
- V : test speed;
- TD : texture depth, which could the mean texture depth (MTD) [6];
- BPN : British Pendulum Number [7];
- a_i ($i = 1, \dots, 6$) : constants to be obtained from fitting.

According to this author, the formula (1) is a simplification of the general formulation (formula (2)).

Leu and Henry [2] proposed the following formula for the exponential shape:

$$\mu = c_0 \exp(c_1 V) \quad (4)$$

Where

- μ : coefficient of friction;
- V : test speed;
- c_0 : constant related to the surface microtexture, characterized indirectly by BPN;
- c_1 : constant related to the surface macrotexture, characterized by MTD.

Since the PIARC experiments in 1992, a new constant has been defined $S_p = -1/c_1$ and called “speed constant”. The Leu and Henry model is referred to now as the “PIARC” model.

Few works mentioned the inverse-S shape, compared with those dealing with the linear and exponential ones. A very important friction-measurement program was carried out within the frame of the BRITE EURAM project entitled “Vehicle-Road-Tire Interaction” (VERT) including various influential factors such as tire types, road surfaces, water thickness, etc. Based on the observed shape of the friction – speed curves, La Torre and Domenichini [3] proposed the following formula:

$$\mu = \mu_{\text{ref}} \cdot \left(b_0 + \frac{b_1}{1 + b_2 e^{(b_3 + b_4 V)}} \right) \quad (5)$$

Where

- μ : coefficient of friction;
- μ_{ref} : “reference” coefficient of friction measured under specific conditions;
- V : test speed;
- b_i ($i = 0, \dots, 4$) : constants to be obtained from fitting.

The constants b_i were related to the water depth, the tire tread depth and the road surface macro- and microtexture. Fittings were performed for μ obtained at the maximum of the friction – wheel slip curve (μ_{peak}) (Fig. 3) and in full locked-wheel condition (μ_{locked}).

The wheel slip is defined by the following formula:

$$\kappa = \frac{V - R\omega}{V}$$

Where

κ : slip;

V: speed;

R: tire radius;

ω : angular velocity of the tire.

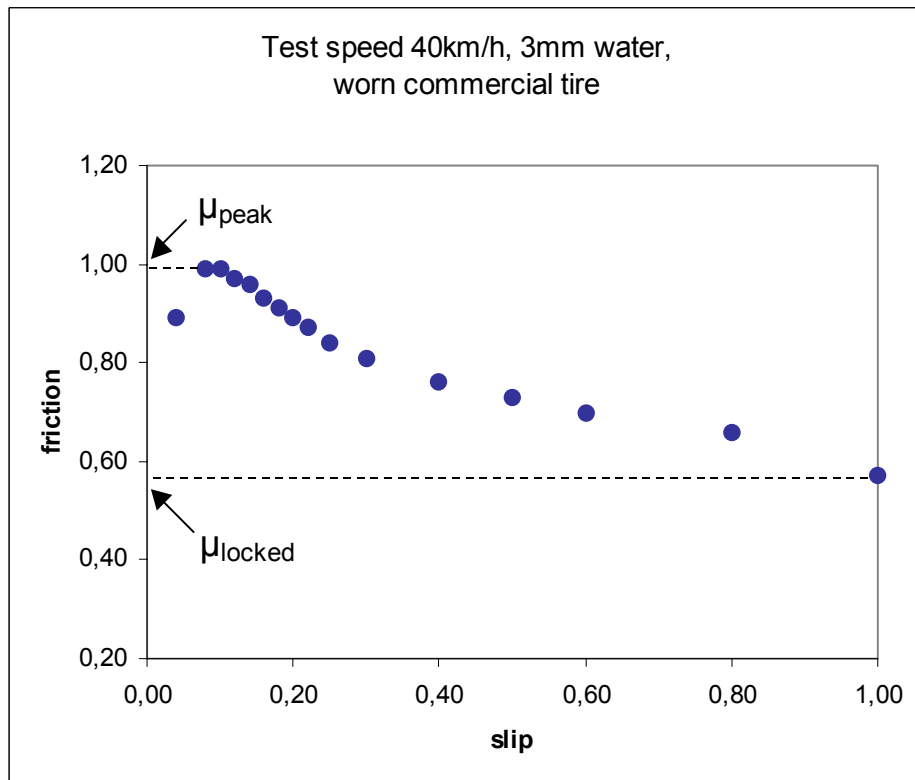


Figure 3. Example of friction – wheel slip curve
(Data source: CETE Lyon)

3- LUBRICATED FRICTION AND THE STRIBECK CURVE

In tribology, the division of the tire/road contact area corresponds to three lubrication regimes:

- The zone 1 corresponds to the “(elasto)hydrodynamic lubrication” regime, where the lubricant (water) separates completely the surfaces;
- The zone 3 corresponds to the “boundary lubrication” regime, where the lubricant is still present at the interface, but its thickness is such that direct contact between the surfaces is possible without adhesion;
- The zone 2 corresponds to the “mixed lubrication” regime, where the lubricant supports part of the contact area.

It was found by Stribeck in 1902 (cited in [5]) that all lubrication regimes can be described by the so-called “Stribeck curve” (Fig. 4). The X-axis of this curve is represented by the parameter H :

$$H = \frac{\eta V}{p}$$

Where

V : speed, which can be relative sliding speed depending on the authors;

η : lubricant viscosity;

p : apparent normal pressure.

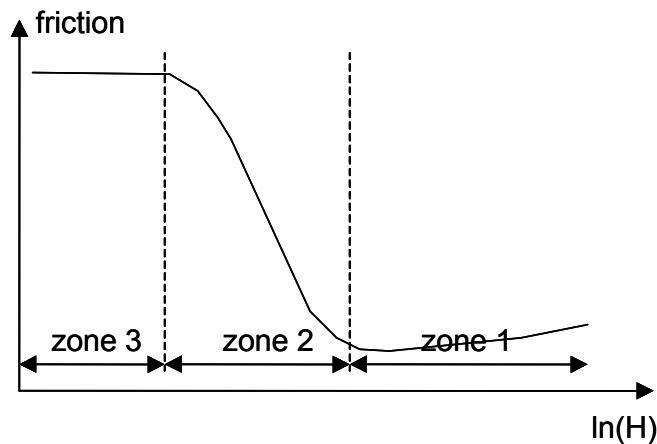


Figure 4. Illustration of the Stribeck curve

The striking point to be noticed is the similar shapes of Stribeck and figure-2b curves. Actually, the exponential tendency becomes linear when V is plotted on logarithm scale. It is then shown that, despite their apparent differences implying various friction models, the commonly observed tire/road friction – speed curves represent part of the general Stribeck curve.

4- NEW FRICTION MODEL BASED ON STRIBECK CURVE DESCRIPTION

The relevance of the Stribeck curve being demonstrated, the question is now how to represent it by mathematical function ?

From reference [3], the formula (5) works well. Other formula can be found in the literature, such as [8][9]:

$$\mu = \alpha + \gamma e^{-\beta(V-\delta)} \quad (6)$$

Or

$$\mu = \mu_c + (\mu_s - \mu_c) \cdot \exp\left(-\left|\frac{V}{V_s}\right|^\alpha\right) + \beta V \quad (7)$$

Where

- μ : coefficient of friction;
- V : test speed;
- μ_c : Coulomb friction [9];
- μ_s : “static” friction [9];
- V_s : “Stribeck” speed [9];
- $\alpha, \beta, \gamma, \delta$: constants to be obtained from fitting.

The formula (6) from [8] is a statistical function called “Gompertz function”. The formula (7) is widely used in tribology research to represent the Stribeck curve [9]. It is then decide to use the formula (7) and adapt it to tire/road friction purpose, giving:

$$\mu = \mu_0 \exp\left[-\left(\frac{V}{V_s}\right)^\alpha\right] + \beta V$$

(8)

Where

- μ_0 : friction at “theoretical” zero speed.

In the figure 2b, the full line represents the formula (8) for $\mu_0 = 0.67$, $V_s = 68\text{km/h}$, $\alpha = 3$ and $\beta = 0$. It can be said that it reproduces well the inverse-S shape. According to [9], the βV term represents a viscous effect, which tends to increase friction (when $\beta > 0$) for increasing speed.

For $\alpha = 1$ and $\beta = 0$, (8) becomes: $\mu = \mu_0 \exp\left(-\frac{V}{V_s}\right)$, which is exactly the PIARC model. The

Stribeck speed is then similar to the PIARC-model speed constant S_p . It is decided to call the new model “modified exponential model”.

5- FITTING OF THE MODIFIED EXPONENTIAL MODEL

5.1- Data

In order to test the ability of the model to fit friction measurements carried out under diverse conditions, two data bases were analyzed:

- Data base from CETE Lyon for VERT project;
- Data base from the Belgian Road Research Center (BRRC) for FERHL "HERMES" project.

In the first data base, friction was measured by a 5th-wheel device called "C35" from free-rolling to full-locked conditions. The test program included: 5 tire types, 3 wheel loads, 3 tire-tread depths, 2 road surfaces, 6 speeds, 3 water-layer thickness. Friction values were recorded as in the figure 3, from which μ_{peak} and μ_{locked} are extracted.

In the second data base, friction was measured by friction-monitoring devices. Fifteen fixed-slip devices were involved in the whole test program. The slips are ranged from 0.14 to 1. Data is an aggregation of 9 cross-test results, each involving in average 6 devices and 6 surfaces. Tests were performed at 3 speeds; the surfaces were wetted by the measuring devices.

For feasibility purpose, the first data base was analyzed for one tire type and μ_{locked} only. For convenience, in the following the first data base will be referred to as "VERT data" and the second as "HERMES data".

5.2- Analysis of VERT data

In the figure 2b, example of fitting results was shown (full line). The fitting was performed for each combination (surface, wheel load, water depth, tire tread depth) using the Excel "solver" function. Speeds are expressed in km/h. Friction values were calculated for each test speed using the formula (8). Values of μ_0 , V_s , α and β were initially entered then optimized by minimizing the sum $\sum_i (\mu_{i,calculated} - \mu_{i,measured})^2$, where the index (i) corresponds to test

speeds. The fitting is accepted when the sum is less than $3 \cdot 10^{-3}$; generally, it was observed that the sum is less than 10^{-3} .

The next step is to relate the fitted model constants to measurable parameters. The first general remark is that β is negligible. Except a few cases, β value is always less than 10^{-4} , meaning that the corresponding friction is not more than 0.01 (the maximum speed is 90km/h). The second general remark is that μ_0 and V_s do not depend on the wheel load; the mean coefficient of variation (ratio mean/standard deviation) when the wheel load changes from 2000N to 5000N is 5%.

It was found that μ_0 depends only on the test-surface texture. Actually, fitted μ_0 values on a given test-surface for various water layer thickness and tire tread depths do not vary more than 10% in term of coefficient of variation. Since the surface macrotexture is similar, the dependency should be related to the microtexture. This is verified by the fact that the average μ_0 values of the test surfaces (0.91 and 0.66 respectively) are of the same order as the surface-BPN values (0.69 and 0.53 respectively). The difference between μ_0 and BPN is for the time being attributed to the rubber properties.

Regarding V_s , since it is similar to the PIARC-model speed constant, it is tempting to relate it to the surface macrotexture. However, within VERT-data frame, it is not possible to perform this analysis since the surface macrotexture is quite similar. In the figure 5, V_s is plotted against the ratio water layer depth/tire tread depth (WD/TD). The choice of this ratio is justified by the fact that it represents roughly the amount of water that affects friction. A general tendency can be seen without distinction between test surfaces: V_s decreases when WD/TD increases. This tendency is logical since WD/TD increases means there is more water in the tire/road contact area and then friction should decrease more rapidly. It can be seen also that V_s seems to stabilize when water saturates the available space provided by tire pattern. Beyond the limit defined by WD/TD = 1, water drainage should depend only on the surface macrotexture.

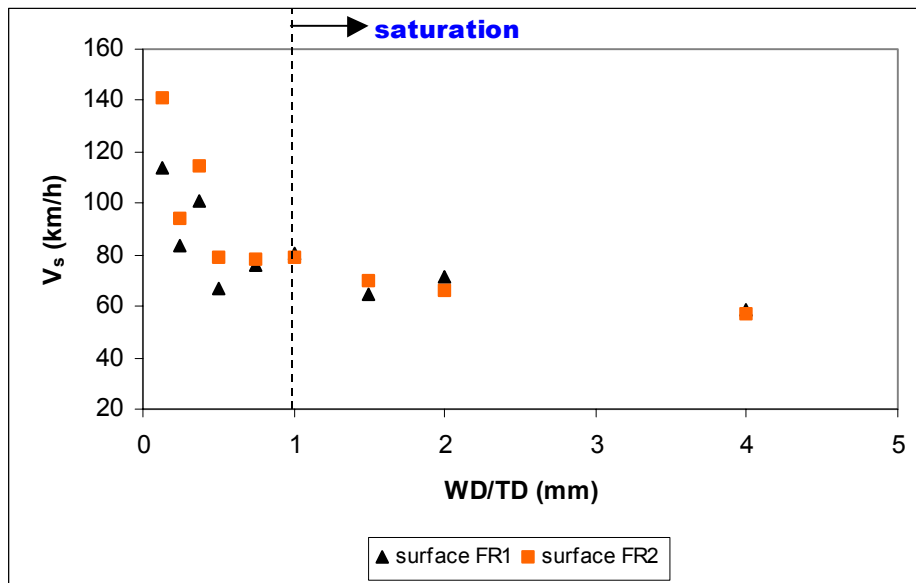


Figure 5. Variation of V_s with WD/TD
(WD: water depth, TD: tire tread depth)

In the figure 6, the exponent (α) is plotted against WD/TD. Despite the great scatter (due to the encircled points), it can be seen that (α) increases with increasing WD/TD, meaning that the shape of the friction – speed curve varies with the ratio WD/TD. Again, beyond the limit WD/TD = 1, (α) stabilizes at 3. It can not be said if whether (α) depends on the test-surface or not.

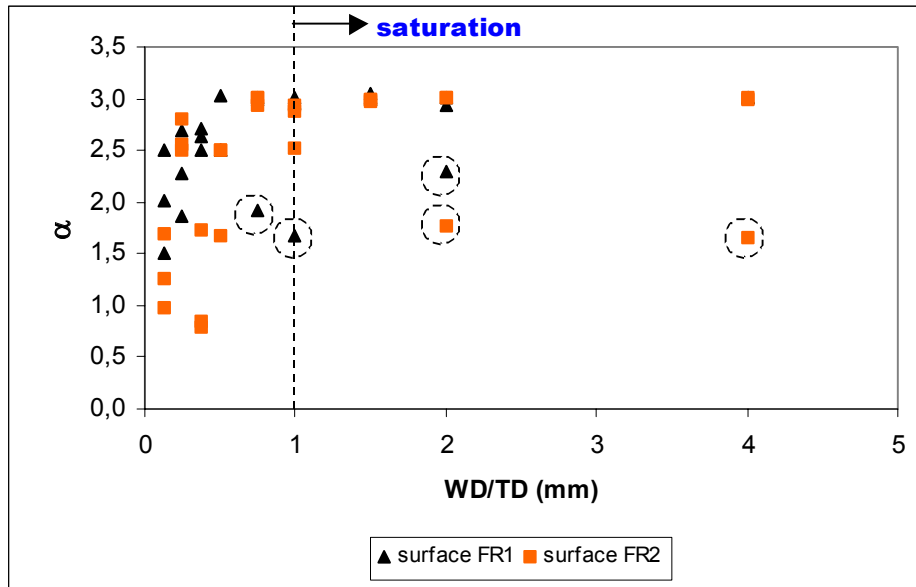


Figure 6. Variation of α with WD/TD
(WD: water depth, TD: tire tread depth)

5.3- Analysis of HERMES data

The main interest of HERMES data is that it comprises a wide range of surface-macrotexture levels and wheel slips.

Based on the analysis of VERT data, the following assumptions were made:

- $\beta = 0$;
- $\alpha = 3$, since all friction-measuring devices, except one, employ blank tire and then the ratio WD/TD should be always superior than 1.

Again, fittings were performed using the Excel solver function and the same acceptability criterion. The results were found to be satisfactory. However, it should be noticed that there are only three speed levels and in almost 85% of cases the PIARC model works well too.

Checking of the relationship between fitted μ_0 and surface BPN is shown in the figure 7 for two friction-measuring devices. It can be seen that:

- μ_0 depends strongly on BPN;
- The difference between μ_0 and BPN depends on the tire properties.

No correspondence was found between μ_0 and surface MPD.

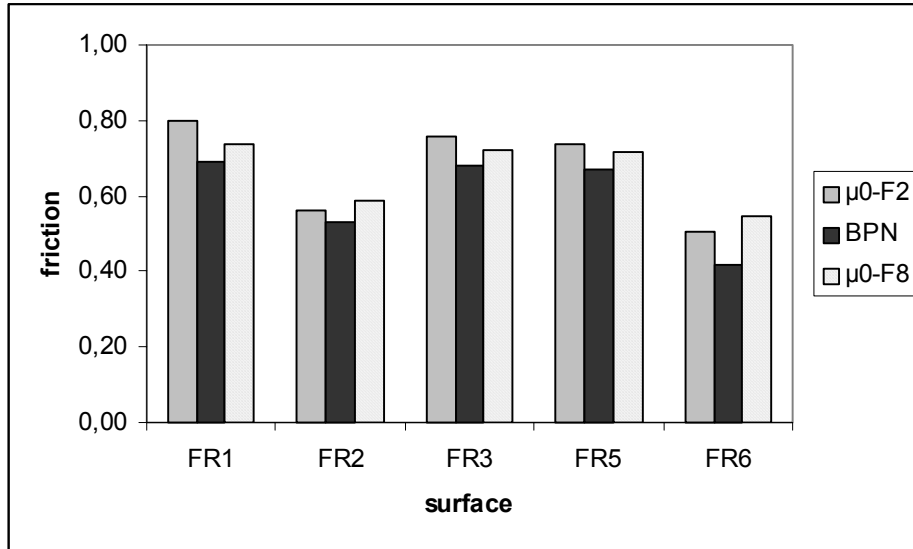


Figure 7. Relationship between μ_0 and surface-BPN for two friction-measuring devices
(F2: locked-wheel ADHERA device, F8: sideways-force ODOLIOGRAPH device)

The relevance of the modified exponential model can be seen through the relationship between V_s and surface macrotexture, characterized by the mean profile depth (MPD) [6]. Examples of V_s – MPD graph for two friction-measuring devices are shown in the figure 8. It can be seen that:

- The relationship is not linear;
- The relationship depends on the friction-measuring device.

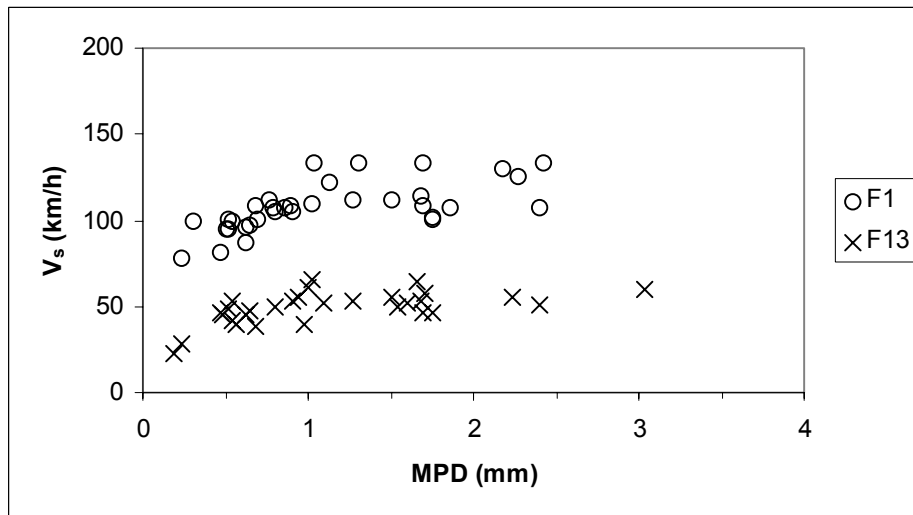


Figure 8. Relationship between V_s and surface-MPD for two friction-measuring devices
(F1: 0.86-slip DWW trailer, F13: TRL SCRIM)

Power function was used to fit observed data, meaning that:

$$V_s = b \cdot \text{MPD}^a$$

Linear regression is performed on $\log(V_s)$ (dependent variable) and $\log(\text{MPD})$ (independent variable), meaning that :

$$\log(V_s) = a \cdot \text{MPD} + \log(b)$$

It was noticed that there is a close relationship between $\log(b)$ and measuring-wheel slip κ . Fitting gives the following formula

$$\log(b) = 0.90 \log(\kappa) + 2.07$$

Then inverse calculations give:

$V_s = 117 \text{MPD}^a \kappa^{0.9}$	(9)
---------------------------------------	-----

Where

a: device-dependent constant.

5.4- Discussions

The modified exponential model requires 4 constants: μ_0 , V_s , α and β . The first constant represents the friction at zero speed. Since the Stribeck curve is stable for very low speeds, μ_0 can actually be determined from friction calculated at any speed between 0 and say 20km/h. The fact that μ_0 does not depend on the surface macrotexture and that μ_0 differs from BPN shows that the low-speed friction should depend only on the surface microtexture and to a lesser degree on the rubber properties.

For V_s , the analysis of HERMES data shows that it can be calculated from surface MPD and measuring-wheel slip. The proposed formula is valid for blank tires. Analysis of VERT data shows that the influence of other factors such as tire tread depth (for patterned tires) or water-layer thickness can be taken into account. Qualitatively, VERT results show that V_s for blank tire represents the minimum value, which then increases when water is further drained away by the tire pattern. However, based on available data, it is not possible at this time to fuse the developed formulae.

For α , it is found from VERT data that this exponent, which defines the shape of the friction – speed curve, depends on the water drainage. Precisely, it increases from 1 (PIARC-model

value) to 3 for decreasing water-drainage action by the tire pattern. For blank tires, the stabilized value is found to be 3. Application to HERMES shows satisfactory results.

For β , zero or very negligible values are found for data presented in this paper. However, analysis of an open-texture surface at LCPC (not presented in this paper) shows that β obtained on this surface can induce significant friction values (0.1 at 30km/h to 0.3 at 90km/h) due to a viscous effect.

6- CONCLUSIONS

In this paper, a new model for friction – speed curves is developed. The model formulation is based on the description of the Stribeck curve, which is widely used in lubricated-friction research. It is shown that this formulation is a generalization of the PIARC model.

The new model called “modified exponential model” requires 4 constants. Based on existing data from VERT and HERMES European projects, it is possible to relate three of them to measurable parameters such as road surface macro- and microtexture, wheel slip, tire tread depth and water layer thickness. Further analyses are needed for the fourth parameter, which describes a viscous effect of friction.

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