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INFLUENCE OF THE ROAD-SURFACE TEXTURE ON THE SPEED DEPENDENCY OF TIRE/ROAD FRICTION

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Abstract :

Tire/wet road friction depends on two road-surface texture scales: the macrotexture (centimeter- to millimeter dimensions) is responsible for the speed dependency of friction, and the microtexture (sub-millimeter dimensions) is responsible for the friction level at any speed.

This paper deals firstly with the description of road-microtexture, the macrotexture scale being well documented. Considering the fact that rubber energy-loss controls tire/wet road friction and that angularity of road-surface asperities influences greatly tire deformation, the second author has proposed a description method derived from the motif-combination technique. This method defines two parameters related to the sharpness of asperity summits and the relative position of these summits.

A model has been then proposed by the first author to describe the friction-speed curve from road-surface macro- and microtexture descriptors, tire-related characteristics (rubber properties, wear) and road wetness. The description is based on the Stribeck curve.

The speed-dependency friction model is applied to the analysis of car-braking tests. Comparisons between calculated and measured friction-coefficients at different braking speeds are presented and discussed.

Key words: friction, texture.

1 Context

The braking capacity of a vehicle depends on friction forces developed in the contact area between the vehicle tires and the road. For longitudinal braking, the friction force F_x is expressed as $F_x = \mu.F_z$, where F_z is the normal load and μ is the tire/road friction coefficient.

The tire/road friction coefficient depends on the wheel slip (κ), expressed as $\kappa = S/V$, where S is the relative speed between the tire and the road (called also slip speed) and V is the vehicle speed. An example of μ - κ curve is shown in the figure 1. It can be seen that this curve comprises two parts corresponding to two braking behaviors:

- In the first part, μ increases to a maximum value called μ_{\max} . The braking is "soft": the more the driver brakes, the more the vehicle decelerates.
- In the second part, μ decreases to a value called μ_{locked} . The braking is "brutal": the wheels are locked and the vehicle slips.

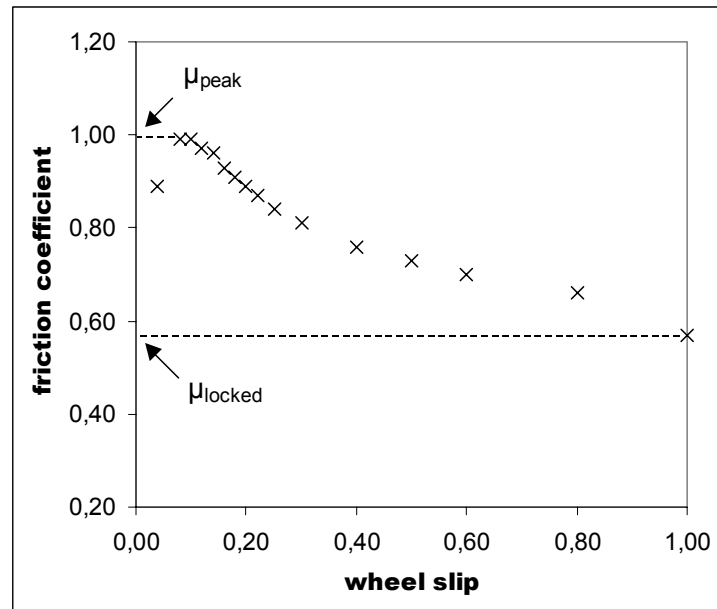


Fig. 1: Example of measurement of friction coefficient as a function of wheel slip.

Since μ_{\max} and μ_{locked} are essential for the knowledge of friction-slip law, and in consequence for vehicle-handling assessment, methods are developed to estimate them whether from wheel kinematics or from road-surface texture.

At LCPC, research has been carried out for more than 30 years to better understand the relationship between road-surface texture and skid resistance. Attempts have been then made to apply this knowledge to the estimation of μ_{\max} and μ_{locked} . This paper presents a synthesis of this work, including a collaboration between LCPC and LTDS.

2 Generalities on tire/road contact

This paper deals with tire/wet road contact, since the friction coefficient on dry road is generally high and slipperiness is mostly problematic on wet roads.

2.1 Road texture scales

Road surface is rough. Two observation scales are defined (Fig. 2):

- The macrotexture is defined as surface irregularities which dimensions are between 0.1 mm and 20 mm vertically and between 0.5 mm and 50 mm horizontally [1].

- The microtexture is defined as surface irregularities which dimensions are between 0.001 mm and 0.5 mm vertically and less than 0.5 mm horizontally [1].

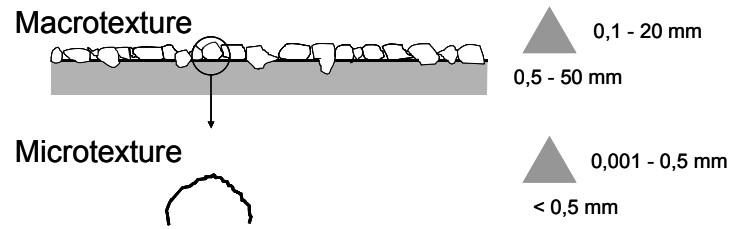


Fig. 2: Road macro- and microtexture scales.

2.2 Tire/road contact area

The tire/wet road contact area is usually divided into three zones (Fig. 3):

- In zone 1, the water separates completely the tire from the road;
- In zone 2, the tire is supported by the water and the road asperities;
- In zone 3, the tire is supported essentially by the road asperities.

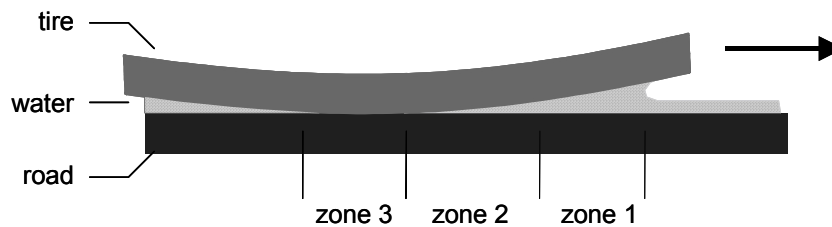


Fig. 3: Scheme of tire/wet road contact.

This scheme shows that friction forces are generated mostly in zone 3. When the vehicle speed increases, the zone-3 size can be reduced due to insufficient water drainage. The friction coefficient varies then with the vehicle speed. It is generally admitted that friction value for a given wheel slip depends on road microtexture and that its variation with speed depends on road macrotexture.

2.3 Friction-speed variation and Stribeck curve

Two examples of friction-speed variation are shown in the figure 4. They show that speed dependency can be different depending on test conditions (tire, water, etc.). Nevertheless, it was shown in [2] that, despite their different shapes, these curves represent part of the Stribeck curve, which is widely employed for lubricated-contact studies (Fig. 5).

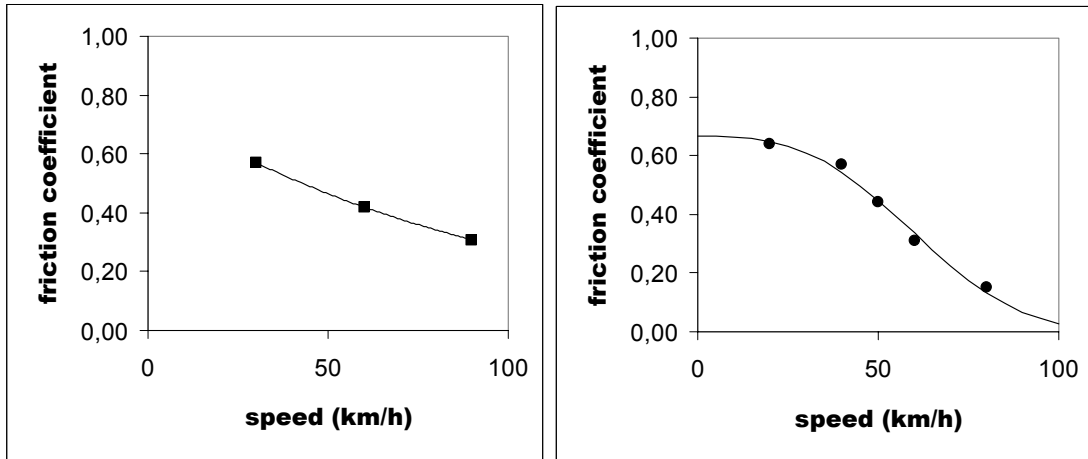


Fig. 4: Examples of friction-speed variation.

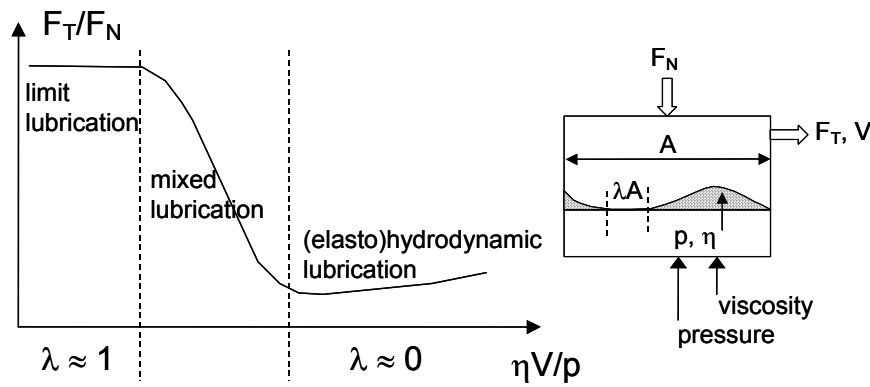


Fig. 5: Lubricated contact and Stribeck curve.

3 Friction estimation

3.1 Approach

Since μ_{max} and μ_{locked} should depend on speed, the following approach is adopted for their estimation:

- model the μ - V curve;
- express the model constants as a function of macro- and microtexture descriptors.

3.2 Friction-speed modeling

The following model was proposed from [2] to describe the variation of tire/road friction with speed:

$$\mu = \mu_0 \cdot \exp\left[-\left(\frac{V}{V_s}\right)^a\right] + bV \tag{1}$$

where μ_0 : friction at theoretical “zero” speed;
 V_s : “Stribeck” speed;
 a, b: “shape” and “viscous” parameters respectively.

The full lines in figure 4 are obtained for (a = 1, b = 0) and (a = 3, b = 0) respectively. It was proved from [2]:

- that μ_0 is related to the road microtexture;
- that V_s is related to the road macrotexture and the wheel slip;
- that a is related to the water thickness above road asperities (WD) and the tire-tread depth (TD);
- that bV term is negligible (roughly 0.01) compared with commonly used tire/wet road friction range ($0.2 < \mu < 0.9$).

In the figure 6, the exponent (a) is plotted against the ratio WD/TD (the symbols correspond to two road surfaces). This ratio takes into account the water-drainage action provided by the tire pattern. Despite some scatters (encircled points), it can be seen that (a) increases with increasing WD/TD, meaning that the shape of friction-speed curves varies with the amount of water. Beyond the limit defined by WD/TD = 1, (a) stabilizes at 3. Physically, WD/TD = 1 expresses the fact that the water saturates completely the tire patterns. Simple fitting (full line in figure 6) shows that (a) can be written as:

$$a = 3 \cdot \left[1 - \exp\left(-k \cdot \frac{WD}{TD}\right) \right] \quad (2)$$

where k: parameter to be obtained from fitting.

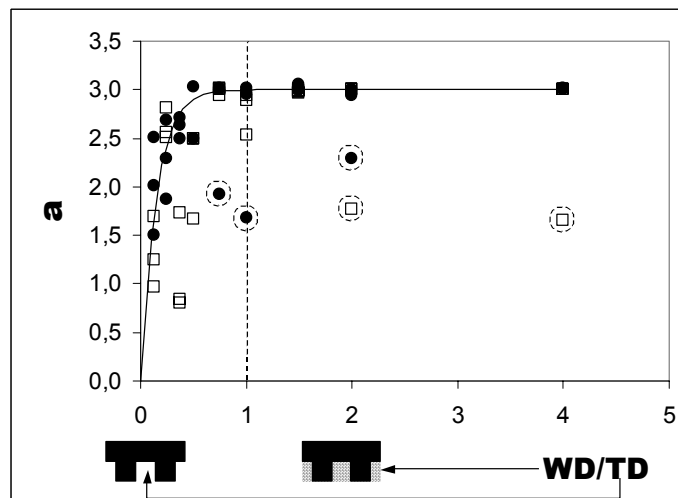


Fig. 6: Variation of “shape” parameter with water depth and tire tread depth.

In the figure 7, variations of Stribeck speed with road macrotexture for two wheel slips are shown. The macrotexture is expressed by the standardized Mean Profile Depth (MPD) [1], which is the distance between the highest profile peaks and the mean profile line. The following formula was found to fit well the measurements [2] (full line in figure 7):

$$V_s = 117 \cdot \text{MPD}^c \cdot k^{0.9} \quad (3)$$

where κ : wheel slip;
 c : vehicle-dependent parameter.

It should be noted that this formula was found for road-monitoring devices which the measuring wheel is generally towed by a vehicle.

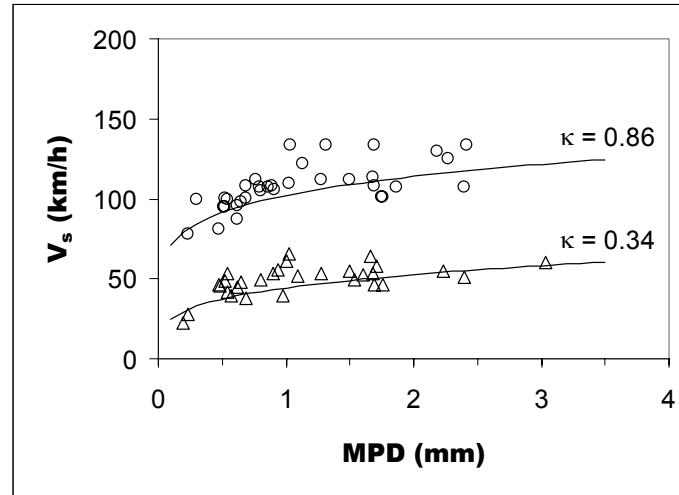


Fig. 7: Variation of “Stribeck” speed with road macrotexture and wheel slip.

3.3 Calculation of μ_0 from road microtexture

This work comprises two parts:

- the microtexture description.
- The calculation of friction from microtexture descriptors using a contact model.

3.3.1 microtexture description

Few works are done on road microtexture compared with those on road macrotexture which descriptors are standardized [1]. Collaboration between LCPC and LTDS was developed few years ago to find out a microtexture description method relevant for tire/road friction purpose. Works are detailed in [3]; they are briefly reminded here.

Example of road profiles is shown in the figure 8. The Y-scale shows that the observed scale is the surface microtexture. The characterization method is based on the following established facts:

- friction is generated only in direct-contact spots between the tire and the road surface.
- the road-asperity shape is the most relevant factor for friction generation.

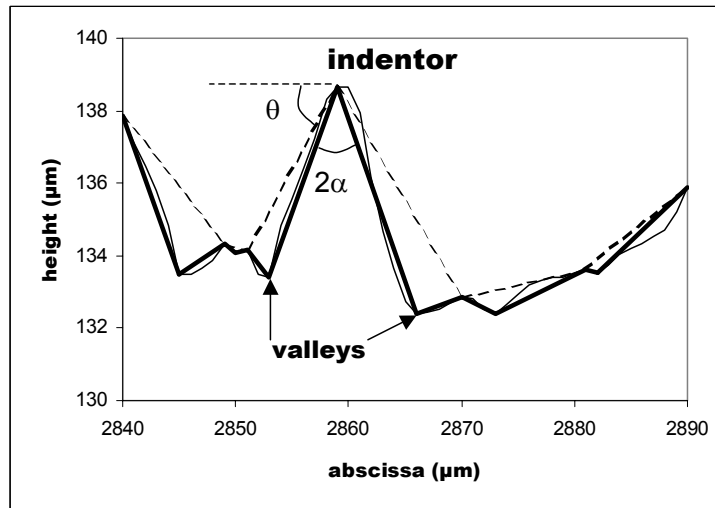


Fig. 8: Road profile and microtexture descriptors.

Road asperities where contact occurs are defined as “indentors” (Fig. 8). An indenter is then part of the road profile between two valleys. The indenter distribution is characterized by two parameters: the shape (cotangent of angle α) and the relief (angle θ). Simple algorithm is developed to detect all profile peaks and valleys called “extremes”.

The characteristic angles are calculated by means of the following formulae:

$$\alpha = \frac{1}{2} \times \left[\tan^{-1} \left| \frac{x_i - x_{i-1}}{z_i - z_{i-1}} \right| + \tan^{-1} \left| \frac{x_{i+1} - x_i}{z_{i+1} - z_i} \right| \right] \quad (4)$$

where:

- x_i : abscissa of the extreme n° (i) (if index (i) is a peak, the indexes (i-1) and (i+1) are valleys);
- z_i : height of the extreme n° (i).

And

$$\theta = \tan^{-1} \left| \frac{z_{j+1} - z_j}{x_{j+1} - x_j} \right| \quad (5)$$

where:

- x_j : abscissa of the peak n° (j);
- z_j : height of the peak n° (j).

Tests performed on laboratory specimens showed that the shape and relief parameters are well correlated to friction (Fig. 9) [3]. Nevertheless, in order to have a predictive tool, these parameters need to be integrated in a model.

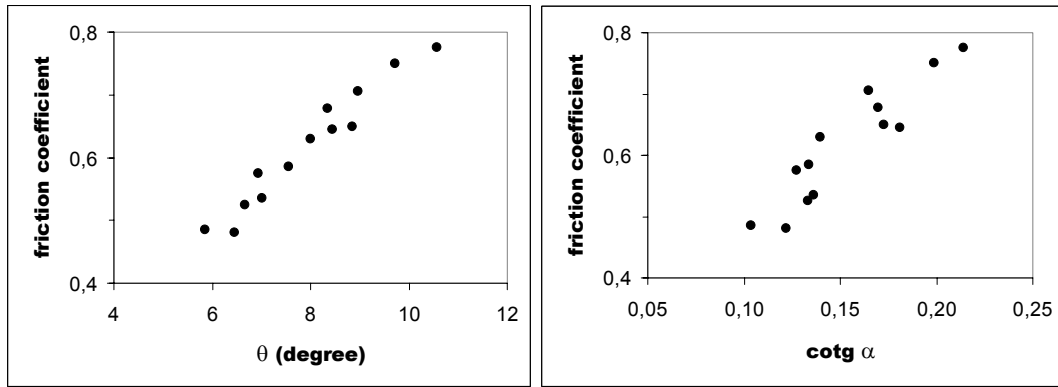


Fig. 9: Relationship between relief (θ) and shape ($\cotg \alpha$) parameters and friction.

3.3.2 contact model

This contact model is developed by M. Stefani (LCPC researcher) with the original aim to simulate the hysteresis effect of friction (energy loss by viscoelastic properties of the rubber). The model geometry represents the contact between a rubber pad and part of a road profile between two peaks called "motif" (Fig. 10). No surface friction (adhesion) is considered. Therefore, the model assumes that friction forces are generated uniquely by deformation of the Kelvin solid representing the rubber pad. The relaxation time of this solid (ratio η/K) is used as the rubber characteristic. It should be noted that the Stefani model is developed for microtexture-study purpose, so the calculated friction is low-speed.

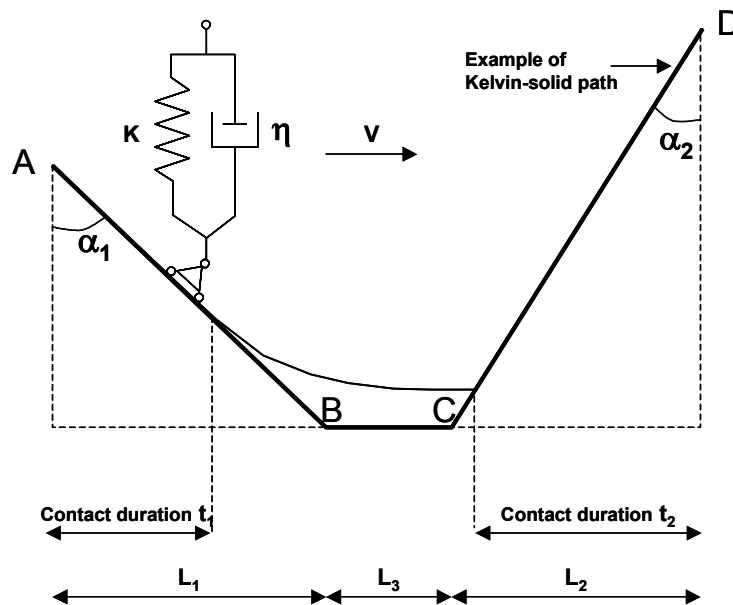


Fig. 10: Geometry of the contact model.

Due to the motif geometry, contact loss can occur between the solid and the motif. Vertical and horizontal forces are calculated and integrated over the contact durations t_1 and t_2 . The ratio between their resultants (f_v and f_h respectively) is defined as a coefficient of friction μ . Details of the calculations can be found in [3].

By setting $L_3 = 0$, this contact model can be coupled with the characterization method developed above to calculate μ from road profiles. The first results [3] obtained on laboratory surfaces composed of coarse aggregates show that two friction values must be considered, which correspond to μ calculated at two scales: the “roughness” scale related to the profile and the “undulation” scale related to its envelop (line connecting all profile peaks). Indentors of the roughness scale are determined from the “bold” line of the figure 8, and those of the undulation scale from the “dotted” line (Fig. 8).

4 Validation

4.1 Methodology

In this paragraph, the method developed in paragraph 3 is applied to the estimation of μ_{locked} at two speeds. The methodology is the following:

- calculate μ_0 from road microtexture-profile measurements;
- calculate V_s from road macrottexture-profile measurements;
- draw the theoretical $\mu_{\text{locked}}-V$ curve.

4.2 Experimental program

Test campaigns were carried out on 30 sites comprising test tracks and trafficked roads (closed during test periods). On each site, the experimental program comprises (Fig. 11):

- Braking tests;
- Road macrottexture measurements;
- Core sampling (four 20 cm-diameter cores) in the braking paths for microtexture measurements in laboratory.

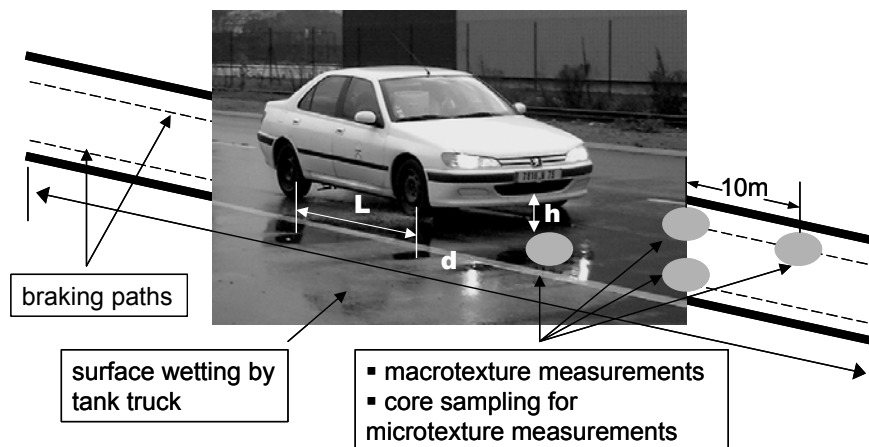


Fig. 11: Experimental program and view of LCPC instrumented vehicle.

The macrottexture was measured using a standardized volumetric method [1]. A known glass bead volume is spread on the road to form a circular patch. Measuring the circle diameter, it can be deduced the mean texture depth. In this paper, this value will be assumed to be also the road profile MPD.

Thirteen microtexture profiles were measured on each core. Their sampling interval is 10 μm and their length is 80 mm (8001 points).

4.3 Braking tests

Braking tests were done by means of a light instrumented vehicle (Peugeot 406) with and without ABS activation. Decelerations are recorded during braking of front wheels from speed V_1 to speed V_2 , then the brake is released. Tests were done for two speed ranges: 90 km/h (V_1) to 70 km/h (V_2), and 60 km/h (V_1) to 40 km/h (V_2).

Friction coefficients are deduced from deceleration measurements using the following formula [4]:

$$\mu = \frac{M \left(\left[\frac{V_1^2 - V_2^2}{2 \cdot d} \right] - \left[A + B \cdot \left(\frac{V_1 + V_2}{2} \right)^2 \right] \right)}{Z_{av} + M \cdot \left(\frac{V_1^2 - V_2^2}{2 \cdot d} \right) \cdot \frac{h}{L}} \quad (6)$$

where:

- μ : friction coefficient;
- M : vehicle mass;
- d : braking distance (Fig. 11);
- V_i ($i = 1, 2$): test speed;
- Z_{av} : load on the front axle;
- h : height of the vehicle center of gravity (Fig. 11);
- L : vehicle wheelbase (Fig. 11).
- A, B : coefficients to be estimated for each vehicle from specific tests.

The friction coefficient is μ_{peak} (respectively μ_{locked}) for braking with ABS (respectively without ABS). The associated speeds are the mean of the speed range: 80km/h for high-speed deceleration tests and 50km/h for low-speed deceleration tests.

4.4 Comparison between theoretical and experimental μ_{locked}

For the calculation of Stribeck speed, formula (3) was used with $\kappa = 1$ (for μ_{locked}) and $c = 0.19$ (empirical value employed for a road-monitoring device using locked measuring wheel).

Since there was no water depth measurement, it was decided to calculate the μ - V curve for two extreme values of the exponent (a) of the formula (1). From the figure 6, it can be said that these values are 1 and 3 respectively. Typical comparison results are shown in the figure 12. The lines represent the theoretical μ - V curves (full line: $a = 1$; dotted line: $a = 3$); they should be the limits since they correspond to extreme values of (a). The points are μ_{locked} values obtained from braking tests. It can be seen that the comparison is satisfactory since the experimental points are inside the theoretical curves.

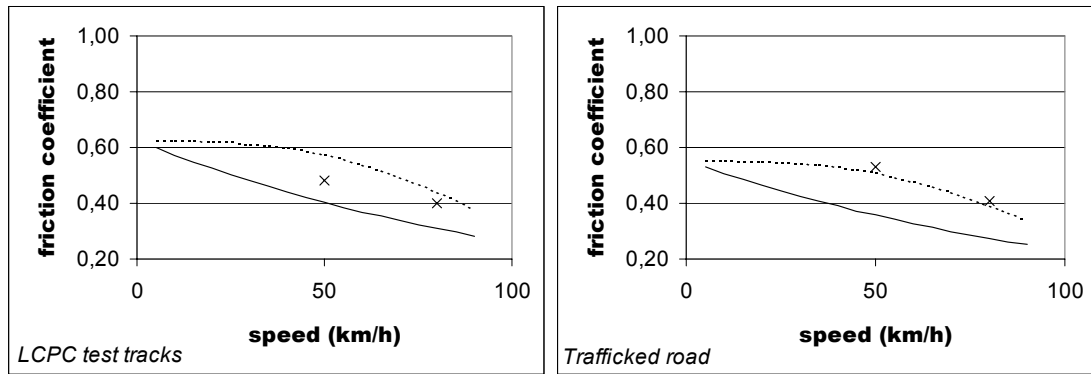


Fig. 12: Experimental μ_{locked} and theoretical $\mu_{locked}-V$ curves (.

5 Conclusions

The main objective of the work presented in this paper is to see if tire/road friction coefficients can be estimated from road surface texture. It was shown from the above paragraphs that this objective could be reached. Knowledge of road macro- and microtexture can be used, via models, to estimate μ_{max} and μ_{locked} , which are two important parameters for vehicle handling assessment.

Further validation results are needed. Nevertheless, the first results are promising enough to look already for possible improvements in texture measurement methods. Macrotexture can be currently measured by on-board sensors. However, efforts are still needed for the development of on-site microtexture measurements.

6 References

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