# Rubber friction on wet and dry road surfaces: The sealing effect

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Rubber friction on wet rough substrates at low velocities is typically 20%–30% smaller than for the corresponding dry surfaces. We show that this cannot be due to hydrodynamics and propose an explanation based on a sealing effect exerted by rubber on substrate "pools" filled with water. Water effectively smoothens the substrate, reducing the major friction contribution due to induced viscoelastic deformations of the rubber by surface asperities. The theory is illustrated with applications related to tire-road friction.

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## I. INTRODUCTION

The study of sliding friction has attracted increasing interest during the last decade thanks also to the development of new experimental and theoretical approaches.[1–4] While some understanding has been gained about the origin and qualitative properties of friction, first-principles calculations of friction forces (or friction coefficients) for realistic systems are in general impossible. The basic reason for this is that friction usually is an interfacial property, often determined by the last few uncontrolled monolayers of atoms or molecules at the interface. An extreme illustration of this is diamond friction: the friction between two clean diamond surfaces in ultrahigh vacuum is huge because of the strong interaction between the surface dangling bonds. However, when the dangling bonds are saturated by monolayers of hydrogen atoms (as they invariably are in real life conditions), friction becomes extremely low.[5] Since most surfaces of practical use are covered by several monolayers of contamination molecules of unknown composition, the quantitative prediction of sliding friction coefficients is generally impossible. An exception to this may be rubber friction on rough surfaces, which is the topic of the present paper.

Rubber friction is a topic of extreme practical importance, e.g., in the context of tires, wiper blades, conveyor belts, and sealings.[6] Rubber friction has several remarkable properties. First, it may be huge, sometimes resulting in friction coefficients much higher than unity. Second, on very rough surfaces—e.g., in the context of a tire sliding on a road surface—it is mainly a *bulk* property of the rubber. That is, the substrate (or road) asperities exert pulsating forces onto the rubber surface which, because of its high internal friction at the appropriate frequencies, results in a large dissipation of energy in the rubber bulk (hysteresis contribution).[7–9] Finally, rubber friction is very sensitive to temperature because of the strong temperature dependence of the viscoelastic bulk properties of rubberlike materials.

Rubber friction on smooth substrates—e.g., a smooth glass surface—has two contributions: namely, an adhesive (surface) and a hysteresis (bulk) contribution.[6,10] The adhesive contribution results from the attractive binding forces between the rubber surface and the substrate. These interactions are often dominated by weak van der Waals forces. However, because of the low elastic moduli of rubberlike materials, even when the applied squeezing force is very gentle this weak attraction may result in a nearly complete contact between the solids at the interface,[11,12] resulting in the large sliding friction force usually observed even for very smooth surfaces.[13] The hysteresis contribution results instead from the substrate roughness (even highly polished surfaces have surface roughness, at least on the nanometer scale).

For very rough surfaces the adhesive contribution to rubber friction will be much smaller than for smooth surfaces, mainly because of the small contact area. For a tire in contact with a road surface, for example, the actual contact area between the tire and substrate is typically only $\sim 1\%$ of the nominal footprint contact area.[7,8] We have shown recently that the observed friction when a tire is sliding on a dry road surface can be calculated accurately by assuming it to be due entirely to internal damping in the rubber (the hysteresis contribution).[7,9] This theory takes into account the pulsating forces acting on the rubber surface from road asperities on many different length scales, from the length scale $\lambda_0 \sim 1$ cm, corresponding to the largest road asperities, down to microasperities characterized by a wavelength $\lambda_c$ of order $\sim 1-10$ $\mu$m (theory shows that shorter-wavelength roughness is unimportant), and gives friction coefficients of order unity, as indeed observed experimentally.

In this paper we study rubber friction at low sliding velocities on wet rough substrates, where it has been observed that the friction typically is 20%–30% smaller than for the corresponding dry surfaces (see Fig. 1 and Refs. 14 and 15). We show that this cannot be a hydrodynamic effect (see especially Appendix A). Expanding on our recent proposal,[16] we put forward an explanation based on the rubber sealing off pools: namely, regions on the substrate filled with water as shown in Fig. 2. The water effectively smoothens the substrate surface and thus reduces the viscoelastic deformation contribution to the rubber friction from the surface asperities.

 

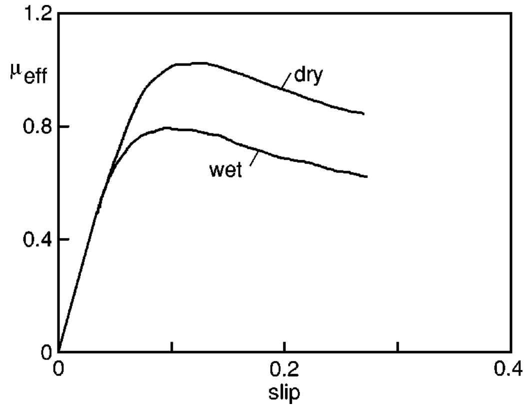


FIG. 1. A typical measured effective friction coefficient as a function of slip for dry and wet road surface. See Sec. III for the definition of the slip.

## II. THEORY

The contribution to rubber friction from the viscoelastic deformation of the rubber surface by the substrate asperities depends only on the complex frequency-dependent viscoelastic modulus $E(\omega)$ of the rubber and on the substrate surface roughness power spectrum $C(q)$, which is defined as follows. Let $h(\mathbf{x})$ be the substrate height profile measured from the average surface plane defined so that $\langle h \rangle = 0$, where $\langle \cdots \rangle$ stands for ensemble averaging or averaging over the total surface. We then have

$$C(q) = \frac{1}{(2\pi)^2} \int d^2x \langle h(\mathbf{x}) h(\mathbf{0}) \rangle e^{-i\mathbf{q}\cdot\mathbf{x}}.$$

We assume that the statistical properties of the substrate surface are isotropic and translationally invariant (within the surface plane), so that $C(q)$ only depends on the magnitude $q = |\mathbf{q}|$ of the wave vector $\mathbf{q}$. The upper curve in Fig. 3 shows the power spectrum calculated from the height profile $h(\mathbf{x})$ measured for an asphalt road using an optical method. The figure shows $C(q)$ as a function of $q$ on a log-log scale. For $q > 1600\ \mathrm{m}^{-1}$, $C(q)$ shows a power law dependence on the wave vector $q$, as expected for a self-affine fractal surface. The fractal dimension of the surface is about 2.2 and the root-mean-square roughness $h_{\mathrm{rms}} \approx 0.3$ mm. For $q < q_0$, $C(q)$ is constant. The roll-off wave vector $q_0$ corresponds to the wavelength $\lambda_0 = 2\pi / q_0 \approx 4$ mm and reflects the largest asperities or sand particles contained in the asphalt.

In general, the hysteresis contribution to rubber friction increases with increasing magnitude of $C(q)$. However, the friction depends on $C(q)$ over a wide range of wave vectors $q$. For example, the rubber friction on asphalt road surfaces depends on $C(q)$ for $q_0 < q < q_1$, where typically $q_0 \approx 10^3\ \mathrm{m}^{-1}$ and $q_1 \approx 10^6\ \mathrm{m}^{-1}$. For a wet road surface, the rubber will seal some surface areas filled with water (pools) as schematically shown in Fig. 2, and this leads to an effective smoothening of the substrate and to a reduced power spectrum. We illustrate this below for the same asphalt road surface for which we showed the power spectrum in Fig. 3 (top curve).

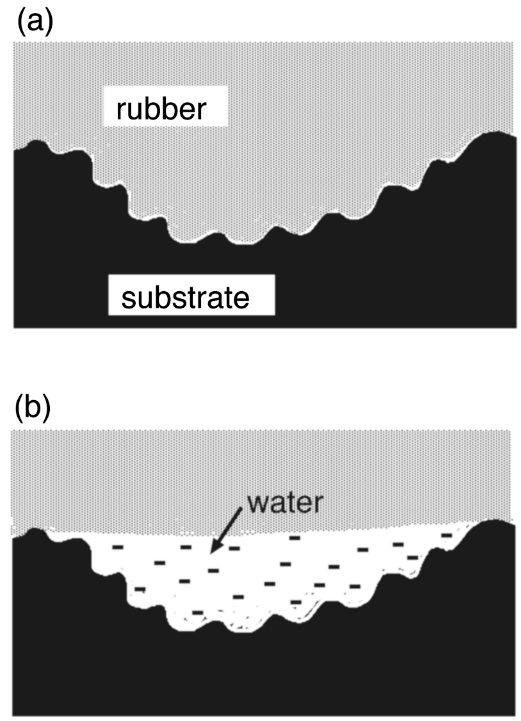


FIG. 2. A rubber block sliding on a rough hard substrate. (a) The rubber penetrates into a large substrate valley and explores the short-wavelength roughness in the valley. The pulsating rubber deformations induced by the short-wavelength roughness contribute to the friction force. (b) On a wet substrate the water trapped in the large valley forms a pool preventing the rubber from penetrating into the valley. It will hence remove the valley contribution to the friction force. This rubber *sealing effect* reduces the sliding friction.

Consider a tire rolling or sliding on a wet road surface. In Appendix A we show in detail that at low velocities (say $v < 30\ \mathrm{km/h}$), there is a negligible hydrodynamic water buildup between the tire and road surface. There is sufficient time for the water to be squeezed from the contact regions between the tire and road surface, *except* for water trapped in road cavities and sealed off by the road-rubber contact at the upper boundaries of the cavities (see Fig. 2). Thus, in what follows we will only focus on the smoothing effect on the road profile by the sealed-off water pools.

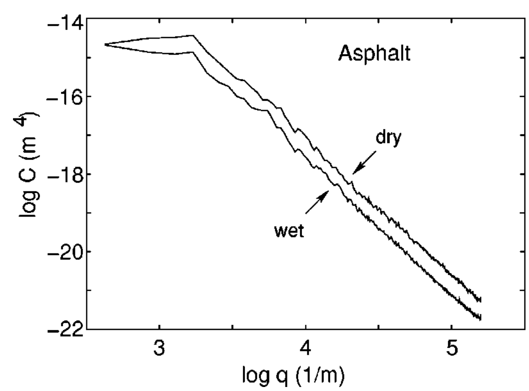


FIG. 3. The logarithm (to base 10) of the surface roughness power spectra $C(q)$ for a dry and a wet asphalt road surface, as a function of the logarithm of the wave vector $q$.

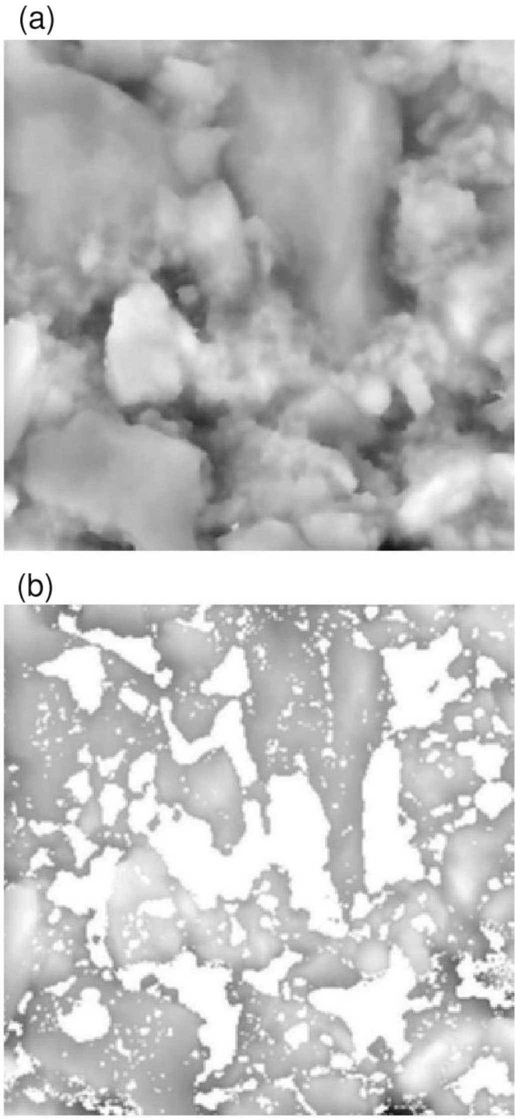


FIG. 4. Optically observed contour line height profile of (a) a dry asphalt road (1.5 cm × 1.5 cm area) and (b) the calculated profile for the same surface area when wet. Deeper asphalt regions are darker, and the water pools in (b) are white.

In Fig. 4(a) we show the height contour lines of a square 1.5 cm × 1.5 cm area of the dry asphalt road. We have calculated the height profile $h'$ shown in Fig. 4(b) (wet surface) numerically. Every valley has been filled with water up to the maximum level where the water still remains confined—i.e., up to the lowest point of the edge surrounding the pool. Any extra addition of water would flow out of the square area. This criterion to fill the surface with water is shown schematically in Fig. 2. From the new height profile $h'(\mathbf{x})$ we can calculate a new power spectrum $C'(q)$ shown by the lower curve in Fig. 3. Now we make the basic assumption (see also below) that when a rubber block slides on the wet surface, the friction force will be determined by the power spectrum $C'(q)$. This implies that the water in the pools is sealed off by the rubber (as indicated in Fig. 2) and cannot get squeezed out. This prevents the rubber from penetrating into the corresponding valley and will reduce the sliding friction by removing contact with the rough walls of the valley.

We notice that our filling criterion is generally not unique, since it depends on the size of the surface area we are considering. In fact it becomes unique (apart from small differences localized at the borders) when the size is much larger than the roll-off wavelength $\lambda_0 \approx 4$ mm, which corresponds to the typical size of the largest pools. Nonetheless, a realistic description requires the surface area to be comparable with the size of the tread block of the tire, while water at the boundaries does not get trapped but it is free to flow away across the channels of the tread pattern. This is indeed the conditions we are adopting through the choice of the size and boundary conditions of the filling procedure. In Appendix B we present the results for another asphalt surface, confirming our results despite the unavoidable statistical noise.

## III. NUMERICAL RESULTS

Now we present numerical results related to tire friction on dry and wet substrates, calculated using the theory presented in Refs. 7 and 9. Neglecting the flash temperature, the friction coefficient is given by[7]

$$\mu = \frac{1}{2} \int dq q^3 C(q) P(q) \int_0^{2\pi} d\phi \cos\phi \, \mathrm{Im} \frac{E(qv\cos\phi)}{(1-\nu^2)\sigma},$$

where

$$P(q) = \frac{2}{\pi} \int_0^\infty dx \, \frac{\sin x}{x} \exp[-x^2 G(q)] = \mathrm{erf}(1/2\sqrt{G}),$$

with

$$G(q) = \frac{1}{8} \int_0^q dq q^3 C(q) \int_0^{2\pi} d\phi \left| \frac{E(qv\cos\phi)}{(1-\nu^2)\sigma} \right|^2,$$

where $\sigma$ is the perpendicular pressure (the load divided by the nominal contact area).

The results presented below have been obtained for a standard tread compound, sliding on the asphalt road introduced in Sec. II. We use the measured complex viscoelastic modulus of the rubber and the power spectra presented in Fig. 3 for the dry and wet road surfaces.

In Fig. 5 we show the kinetic friction coefficient calculated for the dry surface at $T = 60$ °C (a typical tire temperature during driving on a dry road) and for the wet surface at four different temperatures: namely, $T = 30$, 40, 50, and 60 °C. Note that on a wet road the tire temperature is generally lower than on the dry surface, its typical value being ~30 °C. The decreased friction with increasing temperature shown in Fig. 5 is always observed for rubber and results from the shift in the viscoelastic spectrum to higher frequencies with increasing temperature (temperature makes rubber more elastic and less viscous), which in turn reduces the rubber friction.

All modern cars use antiblocking systems (ABS's). In this case during braking the wheels never get fully locked, but the rolling velocity $v_R = \omega R$ is smaller than the forward velocity $v$ of the car, implying that some slip must occur at the tire-road interface. The fundamental characteristic of the tire-

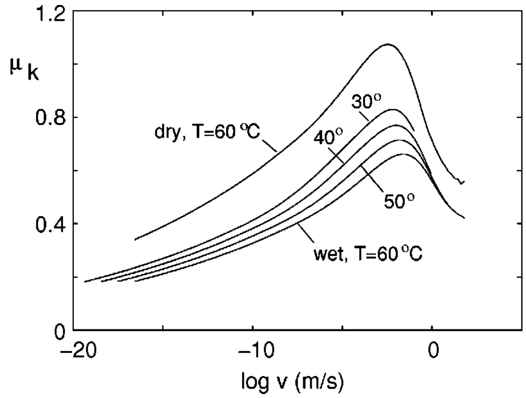


FIG. 5. Kinetic friction coefficient as a function of the logarithm of the sliding velocity, calculated for a standard tread compound and an asphalt substrate.

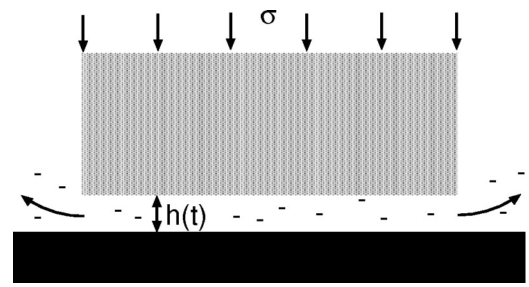


FIG. 6. A tread block squeezed against a smooth flat substrate in a liquid. The surface separation $h(t)$ decreases with increasing time.

road friction relevant for ABS braking is the so called $\mu$-slip curve. Here the slip is defined as $s=(v-v_R)/v$. Hence $s=0$ corresponds to pure rolling and $s=1$ to locked wheel braking. The $\mu$-slip curve depends not only on the rubber-road friction but also on the elastic properties of the tire. Thus, at small slip the tire tread blocks are not slipping relative to the road surface as they first enter the footprint contact area, but will only slip close to the exit of the footprint contact area. The theoretically calculated $\mu$-slip curves (see Fig. 11) for dry and wet surfaces are similar to experimental results (Fig. 1). In particular, the $\mu$-slip curve for the dry and wet surfaces exhibit a similar dependence on the slip as is also observed experimentally,[14,15] but would not be expected if hydrodynamic effects were the origin of the decrease in $\mu_{\text{eff}}$ for wet surfaces. In that case one would expect a much stronger reduction of $\mu_{\text{eff}}$ for large slip.

In Appendix B we present numerical results for another asphalt surface with nearly twice as large surface rms roughness amplitude. Nevertheless, the difference between the friction coefficients for the dry and wet road surfaces is very similar to what we have found above. This shows that the conclusions above are of general validity.

Finally, all sealings leak. This is particularly true in the present case because the upper boundary of a water-filled cavity, which is in contact with the rubber, is not smooth, but has roughness on many length scales, and one cannot expect the rubber to make perfect contact with this region of the substrate. Thus, one expects narrow channels through which water may leak out. As a result, for *very low* car velocities the water may have a negligible influence on the rubber friction. In fact, experiments have shown that the difference in $\mu_{\text{eff}}$ between dry and wet surfaces for velocities $v<1$ m/s is very small.

## IV. DISCUSSION

We have shown that the reduction in rubber friction usually observed when a hard rough road surface becomes wet with water cannot be explained as a hydrodynamic effect, and we have proposed a mechanism involving the rubber sealing off pools filled with water. This leads to an effective smoothening of the substrate and to a lower sliding friction. However, the sealing mechanism may be more complex than outlined above. One can imagine dynamical processes where sealing can occur although not allowed by our procedure. In fact, long-lived trapped-water regions have been observed even when a rubber ball is squeezed against a smooth flat substrate.[17,18] The trapped-water regions sometimes exist even after several hours of stationary contact, therefore reducing the friction on wet surfaces. Another complication is that the water is often located in "deep" valleys which contribute little to the sliding friction, since the rubber is not able to deform enough to fill them out. Hence, our calculation tends to overestimate the influence of such deep valleys to the change in the rubber friction. Since the calculated difference between the friction on dry and wet surfaces is of similar magnitude to that observed, we suggest that the above two effects tend to cancel each other.

Another effect which has been suggested to influence rubber friction on wet surfaces is the dewetting transition,[19,20] which has been studied mainly for very smooth surfaces. The stability of a water film between a rubber block and a flat solid substrate is controlled by the spreading parameter:

$$\Delta\gamma = \gamma_{\text{RS}} - (\gamma_{\text{RL}} + \gamma_{\text{LS}}),$$

where $\gamma_{\text{RS}}$, $\gamma_{\text{RL}}$, and $\gamma_{\text{LS}}$ are the rubber/solid, rubber/liquid, and liquid/solid interfacial free energies per unit area. If $\Delta\gamma>0$, the liquid film (in the absence of a squeezing force) is stable. If $\Delta\gamma<0$, the flat liquid film is unstable and is expected to dewet by nucleation and growth of a dry patch surrounded by a rim, collecting the rejected liquid. However, we do not believe that the dewetting transition is crucial in the context of (rough surface) tire-road friction. First, the dry state should not be the minimum free energy state, since water wets rock surfaces (which usually consist of polar oxides), and this should favor a state with an intercalated water film between the surfaces. Second, the dewetting transition usually involves a thermally activated nucleation process. Thus it should have a strong dependence of temperature, while such strong dependence is not observed for the friction force. Third, the dewetting transition is unlikely to affect the water sealed off by the rubber. Finally, we have argued that the adhesive interaction gives a negligible contribution to the rubber friction force on very rough surfaces so that it is irrelevant whether or not a very thin water film (thickness $h<1$ $\mu$m) is present at the rubber-road asperity contact areas.

## V. SUMMARY AND CONCLUSION

Rubber friction on wet rough substrates at low velocities is typically 20%–30% smaller than for the corresponding dry surfaces. We have shown that this cannot be due to hydrodynamics, and we have propose an explanation based on a sealing effect exerted by rubber on substrate "pools" filled with water. Water effectively smoothens the substrate, reducing the major friction contribution due to induced viscoelastic deformations of the rubber by surface asperities. The theory was illustrated with applications related to tire-road friction.

## ACKNOWLEDGMENTS

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## APPENDIX A: HYDRODYNAMIC SQUEEZE-OUT

Here we present simple arguments to demonstrate that there is negligible hydrodynamic water film buildup at low car velocities, between the road surface and the tread blocks, which is a necessary condition for the sealing mechanism to be relevant. We are interested in water squeeze-out from the rubber-road asperity contact areas, down to a thickness of order $h_c$, where $h_c = h_{\text{rms}}(\lambda_c)$ is the surface root-mean-square roughness amplitude derived from surface roughness wavelength components smaller than $\lambda_c$. This is the shortest surface roughness component which effectively contributes to the rubber friction on the dry surface (typically $\lambda_c \approx 5\ \mu\text{m}$ and $h_c \approx 2\ \mu\text{m}$). We first study the squeeze-out on a length scale larger than the road rms roughness, which typically is of order 1 mm or less. In this case we can neglect the surface roughness and assume that the road surface is completely flat. We consider two limiting cases: namely, a viscous liquid without inertia effects and a liquid with inertia but neglecting the viscosity.

### 1. Role of viscosity

Consider first the influence of the water viscosity on the squeeze-out of the water between a tire tread block and the substrate. We assume first that the substrate is perfectly flat, and we neglect the deformation of the tread block; i.e., the bottom surface of the tread block is considered flat (see Fig. 6). If the tread block is squeezed with the stress $\sigma$ against the substrate in water and if the thickness of the water layer is $h_0$ at time $t=0$, then (neglecting inertia effects) the thickness $h=h(t)$ at time $t$ is given by[21]

$$\frac{1}{h^2(t)} - \frac{1}{h_0^2} = \frac{16t\sigma}{3\mu D^2}, \tag{A1}$$

where $\mu$ is the viscosity and $D$ the width of the tread block. During pure rolling or rolling-sliding with small slip, the tread block stays a time $t \approx W/v$ in the tire foot print area, where $W$ is the length of the foot print contact area and $v$ is the tire rolling velocity. Since we are interested in $h(t) \ll h_0$, it follows from Eq. (A1) that the thickness $h_1$ of the water film at time $t=W/v$ satisfies

$$\frac{1}{h_1^2} \approx \frac{16W\sigma}{3v\mu D^2}$$

or

$$v \approx \frac{16Wh_1^2\sigma}{3\mu D^2}. \tag{A2}$$

If we take $h_1 = 1$ mm, the tread block diameter $D=3$ cm, the footprint length $W=10$ cm, and contact pressure $\sigma = 1$ MPa, we get, for water ($\mu \approx 10^{-3}\ \text{Ns/m}^2$), $v \approx 10^6$ m/s. Thus, the viscosity of the water is irrelevant for the initial squeeze-out down to a thickness of order the root-mean-square amplitude of the substrate roughness.

If we consider pure sliding, the relation between the sliding velocity and the shortest separation between the tread block and the substrate will be[22]

$$v \approx \frac{h_1^2\sigma}{\alpha\mu D}, \tag{A3}$$

where $\alpha$ depends on the ratio of the tread-block substrate separation at the inlet and the exit of the junction. Typically $\alpha \approx 0.1$. Thus, to within a factor of order unity, Eq. (A3) can be obtained from Eq. (A2) if we put $W=D$ and the estimate of $v$ given above still holds.

### 2. Elastohydrodynamic

The analysis above has assumed a flat substrate. However, a road surface has a surface roughness with a typical root-mean-square amplitude of about 1 mm, and the analysis above can only be applied until $h(t) \approx 1$ mm. In studying the influence of surface roughness on the squeeze-out, we consider first the longest-wavelength roughness, with a wavelength determined by the roll-off wave vector $q_0$ via $\lambda_0 = 2\pi/q_0$. When the system is studied at the lateral resolution $\lambda_0$, the contact between the rubber and substrate occurs at randomly distributed asperities with the radius of curvature $R \approx (h_{\text{rms}} q_0^2)^{-1}$. We denote these asperities as macroasperities because they are the largest asperities occurring on the substrate.

Consider a tread block squeezed against a road macroasperity in water (see Fig. 7) and assume that the squeezing force equals $F$ and that the rubber slides with velocity $v$ relative to the asperity. The thickness of the water layer between the asperity and rubber surface can be estimated using the following standard results from elastohydrodynamics[23]:

$$v \approx \frac{0.16}{\mu}\left(\frac{(E^*)^9 F^4 h_1^{20}}{R^{15}}\right)^{1/13}.$$

When the rubber-substrate interface is studied with a lateral resolution of order $\lambda_0$, the area of contact is about 10% of the nominal contact area and the loading force on a macroasperity will typically be $F=100$ N. Using $R=2$ mm, $E^*=1$ MPa,

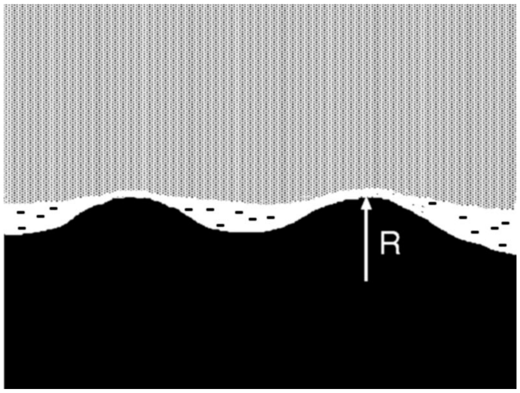


FIG. 7. A tread block squeezed against a rough substrate in a liquid.

and $h_1 = h_c \approx 1$ $\mu$m it follows that $v \approx 200$ m/s. In this study we have neglected the (short-wavelength) roughness on the macroasperity. However, neglecting sealing of water pools, it is easy to see that the inclusion of the short-wavelength roughness in the range $\lambda_c < \lambda < \lambda_0$ can only facilitate (speed up) the squeeze-out of the water, down to the water thickness $\sim h_c$, at the microasperities, characterized by the wavelength $\lambda_c$. This result follows from the fact that the average space between the surfaces at the macroasperity will be much larger than $h_c$.

### 3. Role of inertia

Let us now study the influence of the inertia of the water on the squeeze-out at a tread block. Neglecting the viscosity, the pressure work (per unit time) $-\sigma D^2 \dot{h}$ must be equal to the change in the water kinetic energy per unit time, $\dot{K}$. The kinetic energy is of order

$$K \approx \rho D^2 h \overline{v}^2,$$

where the average velocity $\overline{v} \approx D\dot{h}/h$. Thus we get [with $h(0) = h_0$]

$$-\sigma[h(t) - h_0] \approx \rho D^2 \dot{h}^2 / h$$

or

$$-\sigma[h(t) - h_0]h(t) \approx \rho D^2 \dot{h}^2.$$

We are interested in the case $h(t) \ll h_0$, so we can approximate

$$\sigma h_0 h(t) \approx \rho D^2 \dot{h}^2,$$

which gives the squeeze-out time [i.e., $h(t) = 0$]

$$t \approx D\left(\frac{\rho}{\sigma}\right)^{1/2}. \tag{A4}$$

The time the tread block spends in the footprint area is (for small slip) of order $W/v$ so that Eq. (A4) gives

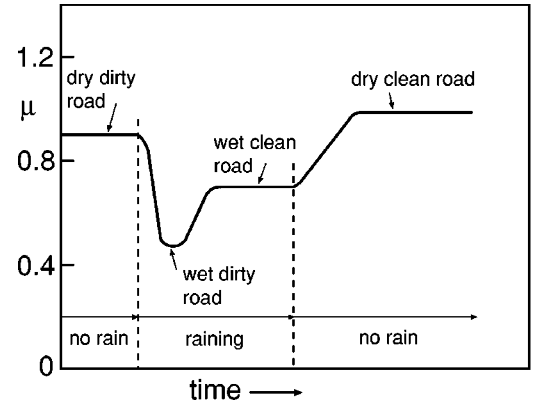


FIG. 8. The dependence of the tire-road friction coefficient on time during rain.

$$v \approx \frac{W}{D}\left(\frac{\sigma}{\rho}\right)^{1/2}. \tag{A5}$$

Using the same numerical values for $W$, $D$, and $\sigma$ as before gives, for water ($\rho = 10^3$ kg/m$^3$), $v \approx 100$ m/s. Thus, if $v \ll 100$ m/s, the inertia of the water will not inhibit the water squeezed out from the interface. When the viscosity is neglected, the total squeeze-out time is finite, but complete squeeze-out (within the framework of the Navier Stokes equations) takes an infinitely long time [see Eq. (1)]. As a result the viscosity effect will always dominate over the inertia effect for very thin liquid films and inertia can be neglected. However, as shown above, for water film thickness $h > 1$ $\mu$m this is not the case and the water viscosity can be neglected.

### 4. Aquaplaning (hydroplaning)

Aquaplaning (or hydroplaning) refers to the limiting case when a tire is completely separated from the road surface by a liquid film. Here we will only consider a tire without a tread pattern. In the case of clean water, aquaplaning is entirely due to the inertia of the water and viscous effects are negligible.[24] This can be seen by applying Eq. (A3) with $D = W \approx 10$ cm equal to the length of the footprint area and

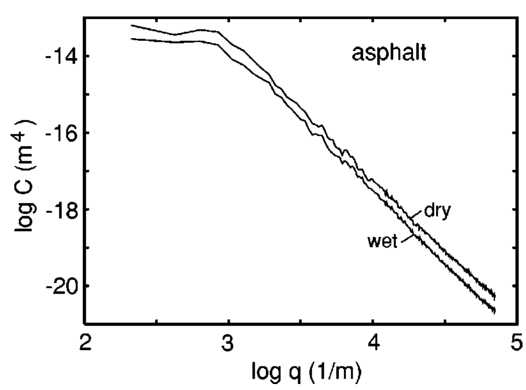


FIG. 9. The logarithm of the surface roughness power spectra $C(q)$ for a dry and a wet asphalt road surface, as a function of the logarithm of the wave vector $q$.

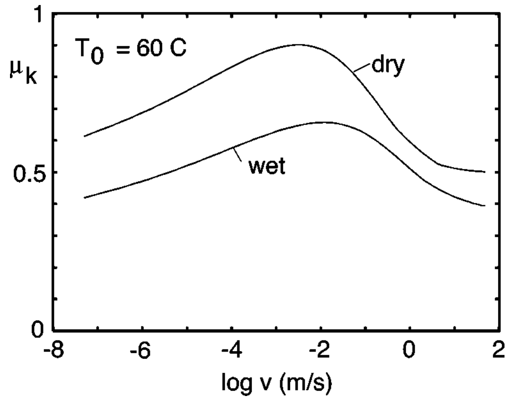


FIG. 10. Kinetic friction coefficient as a function of the logarithm of the sliding velocity, calculated for a standard tread compound and an asphalt substrate.

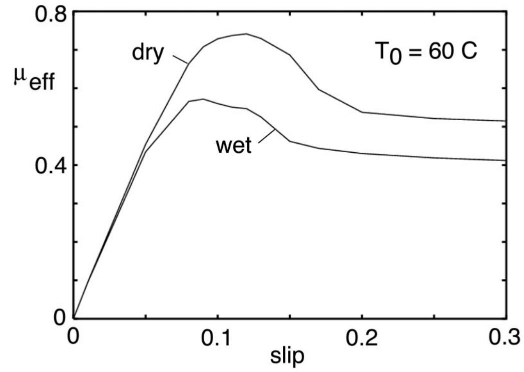


FIG. 11. The effective friction coefficient as a function of slip for dry and wet road surfaces, calculated for a standard tread compound and an asphalt substrate.

$h_1 \approx 1$ mm equal to the amplitude of the road surface roughness. This gives $v \approx 10^5$ m/s—i.e., larger than observed experimentally by a factor of $10^4$. On the other hand, the inertia effect is important even at relatively low velocities. Thus, from Eq. (A5) (with $W=D$),

$$v \approx \left(\frac{\sigma}{\rho}\right)^{1/2},$$

we get $v \approx 20$ m/s. In fact, some tire road lack of contact will occur at the front of the footprint contact area already at lower sliding velocity, but an accurate study of this effect requires taking into account the deformations of the tire and is possible only using advanced finite-element calculations.

Viscous effects may also be important for aquaplaning if the road surface is covered by a high-viscosity fluid—e.g., oil spill or mud—since these fluids may have viscosities $\sim$1000 (or more) times higher than that of water. Many drivers will have noticed that roads are sometimes most slippery when rain begins, and this is caused by rain mixing with road debris, such as dirt (e.g., stone particles or rubber wear particles) and oil, creating an effective high-viscosity lubricant (similar to clay mixed with water) that will decrease the coefficient of friction (see Fig. 8). The coefficient of friction will be particularly low after long time periods, due to the buildup of road debris. As Fig. 8 shows, the coefficient of friction between the road surface and the tire will increase as the rain washes away the road debris. The maximum friction will result when the road has dried, as it is now free from particle contamination (the particles have been washed away by the rain).

To summarize, we have shown that the water viscosity is irrelevant for squeeze-out (unless the effective viscosity is strongly enhanced by contamination), while the water inertia will be important for sufficiently high sliding or rolling velocities. However, for thin water films (less than the tread height), where aquaplaning will not occur, for velocities below, say, $\sim$30 km/h, the water inertia effect can also be neglected, and the only way the water will affect the rubber friction is via the sealing effect.

## APPENDIX B: RESULTS FOR ANOTHER ASPHALT SURFACE

To demonstrate the general nature of the results presented above, here we present results for a second asphalt road with nearly twice as large rms roughness amplitude as the for asphalt surface used above. In Fig. 9 we show the power spectra for the dry and wet asphalt surfaces. Figure 10 shows the kinetic friction coefficient as a function of the logarithm of the sliding velocity both for the dry and wet surfaces.

Figure 11 shows the effective friction coefficient as a function of the slip. The figure is obtained from a computer simulation, where the motion of a single tread block in the tire-road footprint contact area is studied. However, a more realistic calculation involving all the tread blocks coupled to each other (indirectly) via the car cass elasticity, should give a similar result. The $\mu$-slip curves presented in the figure are in good qualitative agreement with typical measured $\mu$-slip curves and show a similar reduction in the friction as the kinetic friction coefficients shown in Fig. 10.


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