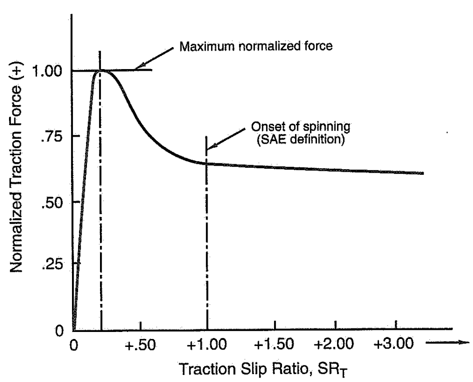

Figure 2.16 Typical traction—slip ratio curve; slip angle = 0°.

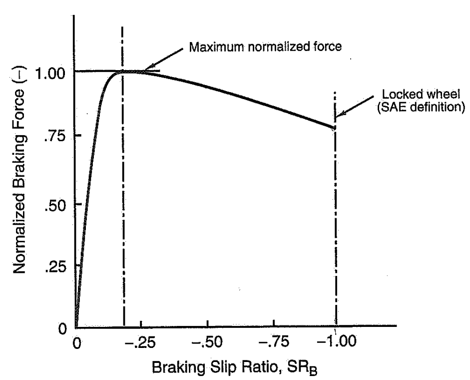

Figure 2.17 Typical braking—slip ratio curve; slip angle = 0°.

taneous basis, the Calspan TIRF uses the loaded radius R_ℓ, the height of the axle above the moving belt, and defines slip ratio as

$$SR = \frac{\Omega R_\ell}{V} - 1$$

When $\alpha \neq 0$, V must be replaced by $V\cos\alpha$ for both traction and braking definitions (see next section).

Definitions of Slip Ratio

A variety of slip ratio definitions are used worldwide. The following terms are used (some for just this section)

R_ℓ = height of the axle above the belt (road surface), loaded radius
R_e = effective rolling radius for free rolling at zero slip angle, from revs/mile
Ω = wheel angular velocity, radians per second
V = speed of the axle over the roadway, or belt surface speed
α = slip angle
S, S_x, SR, K_x, σ_x, S_t, S_b, S_D = alternate definitions of slip ratio

The SAE J670 definition (Ref. 1) is

$$S = \left(\frac{\Omega R_e}{V\cos\alpha}\right) - 1$$

Calspan TIRF definition is

$$SR = \left(\frac{\Omega R_\ell}{V\cos\alpha}\right) - 1$$

An early definition used by Goodyear is

$$S_x = 1 - \left(\frac{V\cos\alpha}{\Omega R_e}\right)$$

Pacejka in Ref. 113 uses

$$\text{Practical slip quantity, } K_x = \left(\frac{\Omega R_e}{V\cos\alpha}\right) - 1$$

$$\text{Independent slip quantity, } \sigma_x = \left(\frac{V\cos\alpha}{\Omega R_e}\right) - 1$$

Sakai in Ref. 136 uses

$$\text{Traction, } S_t = \left(\frac{V\cos\alpha}{\Omega R_e}\right) - 1$$

$$\text{Braking, } S_b = 1 - \left(\frac{\Omega R_e}{V\cos\alpha}\right)$$

Dugoff, Fancher and Segel use the following in Ref. 42:

$$S_D = 1 - \left(\frac{\Omega R_e}{V\cos\alpha}\right)$$

Relationships among the various definitions of slip ratio follow:

$$S = K_x = -S_D = -S_b$$

$$S_x = -\sigma_x = -S_t$$

$$S = \frac{S_x}{1 - S_x} = \frac{-\sigma_x}{1 + \sigma_x}$$

$$S_x = \frac{S}{1 + S}$$

The SAE definition of slip ratio, S, may be computed from the Calspan TIRF definition, SR, as follows:

Let R_0 be the loaded radius for *free rolling at zero slip angle* for a corresponding speed and load. Also, let SR_0 be the corresponding slip ratio according to the TIRF definition. The effective rolling radius for free rolling at the same load and speed is

$$R_e = \frac{R_0}{1 + SR_0}$$

Then, for the case of nonzero slip angle and traction or braking, the SAE definition of slip ratio is given by

$$S = \left(\frac{\Omega R_e}{V\cos\alpha}\right) - 1 = \left(\frac{R_e}{R_\ell}\right)(1 + SR) - 1$$

where R_ℓ is the loaded radius and SR is the TIRF measurement of slip ratio. It is noted that $\Omega = \pi(\text{rpm})/30$, where rpm is that of the test wheel.

2.4 Combined Operation

For the race driver, the effect of traction and braking forces under cornering conditions is important. Although braking is initiated on the straight prior to a corner, it is generally carried on into the turn. Similarly, tractive effort may begin after the turn apex and continue onto the straight.

Sakai Data Plots

Comprehensive data on lateral and longitudinal force as a function of slip angle and slip ratio is relatively rare. Few facilities are available to run a comprehensive set of these tests, which are time consuming and costly. One published set of data (Ref. 136) was obtained by Sakai at the Japan Automobile Research Institute (JARI). This data was taken on a small passenger car tire at a load of 400 kg (882 lb.) and a speed of 20 km/h (12.4 mph). Although the tire and operating conditions are far from those of racing, this data gives a qualitative feel for the effects of combined slip angle and slip ratio. To a first order, tire forces/moments are independent of speed.

In this data, Sakai defines longitudinal force as positive rearward (braking) and lateral force as positive to the right (right-hand turn). He defines two slip ratios, as described in the above tabulation of slip ratio definitions. The following table shows the difference between the SAE and Sakai definitions of slip ratio:

Slip condition	Sakai	SAE
Free rolling	0.0	0.0
Locked wheel braking	+1.0	−1.0
"Spinning" (2 × free rolling Ω)	−0.5	+1.0
"Spinning" (infinite Ω)	−1.0	+ ∞

In order to give the reader a good understanding of the effect of combined slip angle/slip ratio on tire forces, four plots have been made from Sakai's published data. **These are presented using his sign convention and his definitions of slip ratio.**

Figure 2.18 shows the effect of slip angle on the relationship between the traction/braking forces and slip ratio. To reach peak traction/braking forces requires a higher and