CHAPTER 1

MECHANICS OF PNEUMATIC TIRES

Aside from aerodynamic and gravitational forces, all other major forces and moments affecting the motion of a ground vehicle are applied through the running gear–ground contact. An understanding of the basic characteristics of the interaction between the running gear and the ground is, therefore, essential to the study of performance characteristics, ride quality, and handling behavior of ground vehicles.

The running gear of a ground vehicle is generally required to fulfill the following functions:

- to support the weight of the vehicle
- to cushion the vehicle over surface irregularities
- to provide sufficient traction for driving and braking
- to provide adequate steering control and direction stability.

Pneumatic tires can perform these functions effectively and efficiently; thus, they are universally used in road vehicles, and are also widely used in off-road vehicles. The study of the mechanics of pneumatic tires therefore is of fundamental importance to the understanding of the performance and characteristics of ground vehicles. Two basic types of problem in the mechanics of tires are of special interest to vehicle engineers. One is the mechanics of tires on hard surfaces, which is essential to the study of the characteristics of road vehicles. The other is the mechanics of tires on deformable surfaces (unprepared terrain), which is of prime importance to the study of off-road vehicle performance.
The mechanics of tires on hard surfaces is discussed in this chapter, whereas the behavior of tires over unprepared terrain will be discussed in Chapter 2.

A pneumatic tire is a flexible structure of the shape of a toroid filled with compressed air. The most important structural element of the tire is the carcass. It is made up of a number of layers of flexible cords of high modulus of elasticity encased in a matrix of low modulus rubber compounds, as shown in Fig. 1.1. The cords are made of fabrics of natural, synthetic, or metallic composition, and are anchored around the beads made of high tensile strength steel wires. The beads serve as the "foundations" for the carcass and provide adequate seating of the tire on the rim. The ingredients of the rubber compounds are selected to provide the tire with specific properties. The rubber compounds for the sidewall are generally required to be highly resistant to fatigue and scuffing, and styrene–butadiene compounds are widely used [1.1]. The rubber compounds for the tread vary with the type of tire. For instance, for heavy truck tires, the high load intensities necessitate the use of tread compounds with high resistance to abrasion, tearing, and crack growth, and with low hysteresis to reduce internal heat generation and rolling resistance. Consequently, natural rubber compounds are widely used for truck tires, although they intrinsically provide lower values of coefficient of road adhesion, particularly on wet surfaces, than various synthetic rubber compounds universally used for passenger car and racing car tires [1.1]. For tubeless tires, which have become dominant, a thin layer of rubber with high impermeability to air (such as butyl rubber compounds) is attached to the inner surface of the carcass.

The load transmission of a pneumatic tire is analogous to that of a bicycle wheel, where the hub hangs on the spokes from the upper part of the rim, which in turn is supported at its lower part by the ground. For an inflated pneumatic tire, the inflation pressure causes tension to be developed in the cords comprising the carcass. The load applied through the rim of the wheel hangs primarily on the cords in the sidewalls through the beads.

The design and construction of the carcass determine, to a great extent, the characteristics of the tire. Among the various design parameters, the geometric dispositions of layers of rubber-coated cords (plies), particularly their directions, play a significant role in the behavior of the tire. The direction of the cords is usually defined by the crown angle, which is the angle between the cord and the circumferential center line of the tire, as shown in Fig. 1.1. When the cords have a low crown angle, the tire will have good cornering characteristics, but a harsh ride. On the other hand, if the cords are at right angle to the centerline of the tread, the tire will be capable of providing a comfortable ride, but poor handling performance.

A compromise is adopted in a bias-ply tire, in which the cords extend diagonally across the carcass from bead to bead with a crown angle of ap-

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1 Numbers in brackets designate references at the end of the chapter.
Fig. 1.1 Tire construction. (a) Bias-ply tire. (b) Radial-ply tire.
proximately 40°, as shown in Fig. 1.1(a). A bias-ply tire has two plies (for light-load tires) or more (up to 20 plies for heavy-load tires). The cords in adjacent plies run in opposite directions. Thus, the cords overlap in a diamond-shaped (criss-cross) pattern. In operation, the diagonal plies flex and rub, thus elongating the diamond-shaped elements and the rubber-filler. This flexing action produces a wiping motion between the tread and the road, which is one of the main causes of tire wear and high rolling resistance [1.2, 1.3].

The radial-ply tire, on the other hand, is constructed very differently from the bias-ply tire. It was first introduced by Michelin in 1948 and has now become dominant for passenger cars and trucks and increasingly for heavy-duty earth-moving machinery. However, the bias-ply tire is still in use in particular fields, such as cycles, motorcycles, agricultural machinery, and some military equipment. The radial-ply tire has one or more layers of cords in the carcass extending radially from bead to bead, resulting in a crown angle of 90°, as shown in Fig. 1.1(b). A belt of several layers of cords of high modulus of elasticity (usually steel or other high-strength materials) is fitted under the tread, as shown in Fig. 1.1(b). The cords in the belt are laid at a low crown angle of approximately 20°. The belt is essential to the proper functioning of the radial-ply tire. Without it, a radial-ply carcass can become unstable since the tire periphery may develop into a series of buckles due to the irregularities in cord spacing when inflated. For passenger car tires, usually there are two radial plies in the carcass made of synthetic material, such as rayon or polyester, and two plies of steel cords and two plies of cords made of synthetic material, such as nylon, in the belt. For truck tires, usually there is one radial steel ply in the carcass and four steel plies in the belt. For the radial-ply tire, flexing of the carcass involves very little relative movement of the cords forming the belt. In the absence of a wiping motion between the tire and the road, the power dissipation of the radial-ply tire could be as low as 60% of that of the bias-ply tire under similar conditions, and the life of the radial-ply tire could be as long as twice that of the equivalent bias-ply tire [1.3]. For a radial-ply tire, there is a relatively uniform ground pressure over the entire contact area. In contrast, the ground pressure for a bias-ply tire varies greatly from point to point as tread elements passing through the contact area undergo complex localized wiping motion.

There are also tires built with belts in the tread on bias-ply construction. This type of tire is usually called the bias-belted tire. The cords in the belt are of materials with a higher modulus of elasticity than those in the bias-plies. The belt provides high rigidity to the tread against distortion, and reduces tread wear and rolling resistance in comparison with the conventional bias-ply tire. Generally, the bias-belted tire has characteristics midway between those of the bias-ply and the radial-ply tire.

In the United States, the Department of Transportation requires tire manufacturers to provide information on tire dimensions and ratings on the side-
wall of every tire. For instance, for a tire “P185/70 R14 87S,” “P” indicates a passenger car tire; “185” is the nominal width of the cross section in millimeters; “70” is the aspect ratio, which is the ratio of the height of the sidewall to the cross-sectional width; “R” stands for radial-ply tire; “14” is the rim diameter in inches; “87” is a code indicating the maximum load the tire can carry at its maximum rated speed; “S” is a speed rating which indicates the maximum speed that the tire can sustain without failure, S—112 mph (180 km/h), T—118 mph (190 km/h), H—130 mph (210 km/h), V—149 mph (240 km/h), Z—149 mph (240 km/h) or more. Traction and temperature capabilities are indicated on a scale from A to C, A being the best and C the worst. The traction rating is based on straight-line stopping ability on a wet surface. The temperature rating is an index of the tire’s ability to withstand the heat that high speeds, heavy loads, and hard driving generate. Tread-wear index is an indication of expected tire life. It is rated against a reference tire with an index of 100. For instance, a tread-wear rating of 420 means that the tire should last 4.2 times as long as the reference tire. A tread-wear index of 180 is considered to be quite low and an index of 500, quite high.

Although the construction of pneumatic tires differs from one type to another, the basic problems involved are not dissimilar. In the following sections, the mechanics fundamental to all types of tire will be discussed. The characteristics peculiar to a particular kind of tire will also be described.

1.1 TIRE FORCES AND MOMENTS

To describe the characteristics of a tire and the forces and moments acting on it, it is necessary to define an axis system that serves as a reference for the definition of various parameters. One of the commonly used axis systems recommended by the Society of Automotive Engineers is shown in Fig. 1.2 [1.4]. The origin of the axis system is the center of tire contact. The X axis is the intersection of the wheel plane and the ground plane with a positive direction forward. The Z axis is perpendicular to the ground plane with a positive direction downward. The Y axis is in the ground plane, and its direction is chosen to make the axis system orthogonal and right hand.

There are three forces and three moments acting on the tire from the ground. Tractive force (or longitudinal force) \( F_x \) is the component in the X direction of the resultant force exerted on the tire by the road. Lateral force \( F_y \) is the component in the Y direction, and normal force \( F_z \) is the component in the Z direction. Overturning moment \( M_x \) is the moment about the X axis exerted on the tire by the road. Rolling resistance moment \( M_y \) is the moment about the Y axis, and aligning torque \( M_z \) is the moment about the Z axis.

With this axis system, many performance parameters of the tire can be conveniently defined. For instance, the longitudinal shift of the center of normal pressure is determined by the ratio of the rolling resistance moment to
the normal load. The lateral shift of the center of normal pressure is defined by the ratio of the overturning moment to the normal load. The integration of longitudinal shear stresses over the entire contact patch represents the tractive or braking force. A driving torque about the axis of rotation of the tire produces a force for accelerating the vehicle, and a braking torque produces a force for decelerating the vehicle.

There are two important angles associated with a rolling tire: the slip angle and the camber angle. Slip angle $\alpha$ is the angle formed between the direction of wheel travel and the line of intersection of the wheel plane with the road surface. Camber angle $\gamma$ is the angle formed between the $XZ$ plane and the wheel plane. The lateral force at the tire–ground contact patch is a function of both the slip angle and the camber angle.

1.2 ROLLING RESISTANCE OF TIRES

The rolling resistance of tires on hard surfaces is primarily caused by the hysteresis in tire materials due to the deflection of the carcass while rolling. Friction between the tire and the road caused by sliding, the resistance due to air circulating inside the tire, and the fan effect of the rotating tire on the
surrounding air also contribute to the rolling resistance of the tire, but they are of secondary importance. Available experimental results give a breakdown of tire losses in the speed range 128–152 km/h (80–95 mph) as 90–95% due to internal hysteresis losses in the tire, 2–10% due to friction between the tire and the ground, and 1.5–3.5% due to air resistance [1.5, 1.6]. Of the total energy losses within the tire structure, it is found that for a radial truck tire, hysteresis in the tread region, including the belt, contributes 73%, the sidewall 13%, the region between the tread and the sidewall, commonly known as the shoulder region, 12%, and the beads 2%.

When a tire is rolling, the carcass is deflected in the area of ground contact. As a result of tire distortion, the normal pressure in the leading half of the contact patch is higher than that in the trailing half. The center of normal pressure is shifted in the direction of rolling. This shift produces a moment about the axis of rotation of the tire, which is the rolling resistance moment. In a free-rolling tire, the applied wheel torque is zero; therefore, a horizontal force at the tire–ground contact patch must exist to maintain equilibrium. This resultant horizontal force is generally known as the rolling resistance. The ratio of the rolling resistance to the normal load on the tire is defined as the coefficient of rolling resistance.

A number of factors affect the rolling resistance of a pneumatic tire. They include the structure of the tire (construction and materials) and its operating conditions (surface conditions, inflation pressure, speed, temperature, etc.). Tire construction has a significant influence on its rolling resistance. Figure 1.3 shows the rolling resistance coefficient at various speeds of a range of bias-ply and radial-ply passenger car tires at rated loads and inflation pressures on a smooth road [1.7]. The difference in rolling resistance coefficient between a bias-ply and a radial-ply truck tire of the same size under rated conditions is shown in Fig. 1.4 [1.8]. Thicker treads and sidewalls and an increased number of carcass plies tend to increase the rolling resistance because of greater hysteresis losses. Tires made of synthetic rubber compounds generally have higher rolling resistance than those made of natural rubber. Tires made of butyl rubber compounds, which are shown to have better traction and roadholding properties, have an even higher rolling resistance than those made of conventional synthetic rubber. It is found that the rolling resistance of tires with tread made of synthetic rubber compounds and that made of butyl rubber compounds are approximately 1.06 and 1.35 times that made of natural rubber compounds, respectively [1.9].

Surface conditions also affect the rolling resistance. On hard, smooth surfaces, the rolling resistance is considerably lower than that on a rough road. On wet surfaces, a higher rolling resistance than on dry surfaces is usually observed. Figure 1.5 shows a comparison of the rolling resistance of passenger car tires over six road surfaces with different textures, ranging from polished concrete to coarse asphalt [1.10]. The profiles of these six surfaces are shown in Fig. 1.6. It can be seen that on the asphalt surface with coarse sealcoat (surface no. 6) the rolling resistance is 33% higher than that on a new
Fig. 1.3  Variation of rolling resistance coefficient of radial-ply and bias-ply car tires with speed on a smooth, flat road surface under rated load and inflation pressure. (Reproduced with permission from *Automotive Handbook*, 2nd edition, Robert Bosch GmbH, Germany.)

Fig. 1.4  Variation of rolling resistance coefficient of radial-ply and bias-ply truck tires with speed under rated load and inflation pressure. (Reproduced with permission from reference 1.8.)
Fig. 1.5  Variation of tire rolling resistance with pavement surface texture. (Reproduced with permission of the Society of Automotive Engineers from reference 1.10.)

Fig. 1.6  Texture of various types of pavement surface. (Reproduced with permission of the Society of Automotive Engineers from reference 1.10.)
concrete surface (surface no. 2), while on the polished concrete (surface no. 1), it shows a 12% reduction in comparison with that on the new concrete surface.

Inflation pressure affects the flexibility of the tire. Depending on the deformability of the ground, the inflation pressure affects the rolling resistance of the tire in different manners. On hard surfaces, the rolling resistance generally decreases with the increase in inflation pressure. This is because, with higher inflation pressure, the deflection of the tire decreases, with consequent lower hysteresis losses. Figure 1.7 shows the effects of inflation pressure on the rolling resistance of a radial-ply tire (GR78-15), a bias-ply tire, and a bias-belted tire (both G78-15) under various normal loads, expressed in terms of the percentage of the rated load at an inflation pressure of 165 kPa (24 psi) [1.11]. The results were obtained with the inflation pressure being regulated, that is, the pressure was maintained at a specific level throughout the tests. It can be seen that inflation pressure has a much more significant effect on the rolling resistance of the bias and bias-belted tires than the radial-ply tire. On deformable surfaces, such as sand, high inflation pressure results in increased ground penetration work, and therefore higher rolling resistance, as shown in Fig. 1.8 [1.12]. Conversely, lower inflation pressure, while decreasing ground penetration, increases the deflection of the tire and hence internal hysteresis losses. Therefore, an optimum inflation pressure exists for a particular tire on a given deformable surface, which minimizes the sum of ground penetration work and internal losses of the tire.

Inflation pressure not only affects the rolling resistance, but also the tread wear of a tire. Figure 1.9 shows the effects of inflation pressure on tread wear
1.2 ROLLING RESISTANCE OF TIRES

Fig. 1.8 Variation of rolling resistance coefficient with inflation pressure of tires on various surfaces. (Reproduced with permission from reference 1.12.)

Fig. 1.9 Variation of shoulder-crown wear with inflation pressure for radial-ply, bias-ply, and bias-belted car tires. (Reproduced with permission of the Society of Automotive Engineers from reference 1.11.)
of a radial-ply, a bias-ply, and a bias-belted tire [1.11]. The wear rate at 165 kPa (24 psi) is used as a reference for comparison. It can be seen that the effects of inflation pressure on tread wear are more significant for the bias-ply and bias-belted tire than the radial-ply tire.

Rolling resistance is also affected by driving speed because of the increase of work in deforming the tire and of vibrations in the tire structure with the increase in speed. The effects of speed on the rolling resistance of bias-ply and radial-ply passenger car and truck tires are illustrated in Figs. 1.3 and 1.4, respectively. For a given tire under a particular operating condition, there exists a threshold speed above which the phenomenon popularly known as standing waves will be observed, as shown in Fig. 1.10. The approximate value of the threshold speed \( V_{th} \) may be determined by the expression

\[
V_{th} = \sqrt{\frac{F_t}{\rho_t}}
\]

where \( F_t \) is the circumferential tension in the tire and \( \rho_t \) is the density of tread material per unit area [1.13]. Standing waves are formed because, owing to high speed, the tire tread does not recover immediately from distortion originating from tire deflection after it leaves the contact surface, and the residual deformation initiates a wave. The amplitude of the wave is the greatest immediately on leaving the ground, and is damped out in an exponential manner around the circumference of the tire. The formation of the standing wave greatly increases energy losses, which in turn cause considerable heat generation that could lead to tire failure. This places an upper limit on the safe operating speed of tires.

Operating temperature, tire diameter, and tractive force also have effects on the rolling resistance of a tire. Tire temperature affects the rolling resistance in two ways: one is by changing the temperature of the air in the tire cavity, and thereby changing the operating inflation pressure; and the other is by changing the stiffness and hysteresis of the rubber compounds. Figure 1.11 shows the dependence of the rolling resistance on the internal tire temperature for an automobile tire [1.5]. The variation of rolling resistance coefficient with shoulder temperature of a radial-ply passenger car tire is shown in Fig. 1.12 [1.14]. It can be seen that the rolling resistance at a shoulder temperature of \(-10^\circ\text{C}\) is approximately 2.3 times that at \(60^\circ\text{C}\) for the tire examined. It is also found that the shoulder temperature of the tire, and not the ambient

![Fig. 1.10 Formation of standing waves of a tire at high speeds.](image)
1.2 ROLLING RESISTANCE OF TIRES

Fig. 1.11  Effect of internal temperature on rolling resistance coefficient of a car tire. (Reproduced with permission of the Council of the Institution of Mechanical Engineers from reference 1.5.)

Fig. 1.12  Variation of rolling resistance coefficient with shoulder temperature for a car tire P195/75R14. (Reproduced with permission of the Society of Automotive Engineers from reference 1.14.)

temperature, is a basic determining factor of the tire rolling resistance coefficient. The effect of tire diameter on the coefficient of rolling resistance is shown in Fig. 1.13 [1.12]. It can be seen that the effect of tire diameter is negligible on hard surfaces (concrete), but is considerable on deformable or soft ground. Figure 1.14 shows the effect of the braking and tractive effort on the rolling resistance [1.6].
When considering the effects of material, construction, and design parameters of tires on rolling resistance, it is necessary to have a proper perspective of the energy losses in the tire and the characteristics of the tire–vehicle system as a whole. Although it is desirable to keep the rolling resistance as low as possible, it should be judged against other performance parameters, such as tire endurance and life, traction, cornering properties, cushioning ef-
fect, cost, etc. For instance, from the standpoint of rolling resistance, synthetic rubber compounds are less favorable than natural rubber compounds, yet because of significant advantages in cost, tread life, wet-road grip, and tire squeal, they have virtually displaced natural rubber compounds from passenger car tires, particularly for treads. For high-performance vehicles, there may be some advantage for using butyl rubber tires because of the marked gains in traction, roadholding, silence, and comfort, in spite of their poor hysteresis characteristics [1.5].

The complex relationships between the design and operational parameters of the tire and its rolling resistance make it extremely difficult, if not impossible, to develop an analytic method for predicting the rolling resistance. The determination of the rolling resistance, therefore, relies almost entirely on experiments. To provide a uniform basis for collecting experimental data, the Society of Automotive Engineers recommends rolling resistance measurement procedures for various types of tire on different surfaces, which may be found in the SAE Handbook.

Based on experimental results, many empirical formulas have been proposed for calculating the rolling resistance of tires on hard surfaces. For instance, based on the experimental data shown in Fig. 1.3, for radial-ply passenger car tires under rated loads and inflation pressures on a smooth road, the relationship between rolling resistance coefficient $f_r$ and speed $V$ (up to 150 km/h or 93 mph) may be expressed by

$$f_r = 0.0136 + 0.40 \times 10^{-7} V^2$$  \hspace{1cm} (1.1)

and for bias-ply passenger car tires,

$$f_r = 0.0169 + 0.19 \times 10^{-6} V^2$$  \hspace{1cm} (1.2)

where $V$ is in km/h.

Based on the experimental data shown in Fig. 1.4, for the radial-ply truck tire under rated load and inflation pressure, the relationship between the rolling resistance coefficient $f_r$ and speed $V$ (up to 100 km/h or 62 mph) may be described by

$$f_r = 0.006 + 0.23 \times 10^{-6} V^2$$  \hspace{1cm} (1.3)

and for the bias-ply truck tire,

$$f_r = 0.007 + 0.45 \times 10^{-6} V^2$$  \hspace{1cm} (1.4)

where $V$ is in km/h.

The rolling resistance coefficient of truck tires is usually lower than that of passenger car tires on road surfaces. This is primarily due to the higher
inflation pressure used in truck tires (typically 620–827 kPa or 90–120 psi as opposed to 193–248 kPa or 28–36 psi for passenger car tires).

In preliminary performance calculations, the effect of speed may be ignored, and the average value of \( f_r \) for a particular operating condition may be used. The average values of \( f_r \) for various types of tire over different surfaces are summarized in Table 1.1.

### 1.3 TRACTIVE (BRAKING) EFFORT AND LONGITUDINAL SLIP (SKID)

When a driving torque is applied to a pneumatic tire, a tractive force is developed at the tire–ground contact patch, as shown in Fig. 1.15 [1.6]. At the same time, the tire tread in front of and within the contact patch is subjected to compression. A corresponding shear deformation of the sidewall of the tire is also developed.

As tread elements are compressed before entering the contact region, the distance that the tire travels when subject to a driving torque will be less than that in free rolling. This phenomenon is usually referred to as longitudinal slip. The longitudinal slip of the vehicle running gear, when a driving torque is applied, is usually defined by

\[
i = \left( 1 - \frac{V}{r\omega} \right) \times 100\% = \left( 1 - \frac{r_e}{r} \right) \times 100\%
\]  

(1.5)

where \( V \) is the linear speed of the tire center, \( \omega \) is the angular speed of the tire, \( r \) is the rolling radius of the free-rolling tire, and \( r_e \) is the effective rolling radius of the tire, which is the ratio of the linear speed of the tire center to the angular speed of the tire.

<table>
<thead>
<tr>
<th>Road Surface</th>
<th>Coefficient of Rolling Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car tires</td>
<td></td>
</tr>
<tr>
<td>Concrete, asphalt</td>
<td>0.013</td>
</tr>
<tr>
<td>Rolled gravel</td>
<td>0.02</td>
</tr>
<tr>
<td>Tarmacadam</td>
<td>0.025</td>
</tr>
<tr>
<td>Unpaved road</td>
<td>0.05</td>
</tr>
<tr>
<td>Field</td>
<td>0.1–0.35</td>
</tr>
<tr>
<td>Truck tires</td>
<td></td>
</tr>
<tr>
<td>Concrete, asphalt</td>
<td>0.006–0.01</td>
</tr>
</tbody>
</table>

When a driving torque is applied, the tire rotates without the equivalent translatory progression; therefore, $r\omega > V$ and a positive value for slip results. If a tire is rotating at a certain angular speed but the linear speed of the tire center is zero, then in accordance with Eq. 1.5, the longitudinal slip of the tire will be 100%. This is often observed on an icy surface, where the driven tires are spinning at high angular speeds, while the vehicle does not move forward. The definition of longitudinal slip given by Eq. 1.5 is adopted in the analysis of the mechanics of tires in this book.

A definition of longitudinal slip different from that given by Eq. 1.5 appears in some publications. For instance, in the SAE Handbook Supplement, Vehicle Dynamics Terminology J670e [1.4], longitudinal slip is defined as “the ratio of the longitudinal slip velocity to the spin velocity of the straight free-rolling tire expressed as a percentage.” The longitudinal slip velocity is taken as “the difference between the spin velocity of the driven or braked tire and the spin velocity of the straight free-rolling tire.” Both spin velocities are measured at the same linear velocity at the wheel center in the $X$ direction (Fig. 1.2). A positive value of slip results from a driving torque. In essence,
the definition of longitudinal slip $i'$ suggested by the SAE can be expressed by

$$i' = \left( \frac{r\omega}{V} - 1 \right) \times 100\% = \left( \frac{r}{r_e} - 1 \right) \times 100\% \quad (1.6)$$

where $V$, $\omega$, $r$, and $r_e$ are defined in the same way as that for Eq. 1.5.

It should be noted that in accordance with the definition suggested by the SAE, when a tire is rotating at a certain angular speed but the linear speed of the tire center is zero, the longitudinal slip $i'$ of the tire will be denoted as infinite.

As the tractive force developed by a tire is proportional to the applied wheel torque under steady-state conditions, slip is a function of tractive effort. Generally speaking, at first the wheel torque and tractive force increase linearly with slip because, initially, slip is mainly due to elastic deformation of the tire tread. This corresponds to section $OA$ of the curve shown in Fig. 1.16. A further increase of wheel torque and tractive force results in part of the tire tread sliding on the ground. Under these circumstances, the relationship between the tractive force and the slip is nonlinear. This corresponds to section $AB$ of the curve shown in Fig. 1.16. Based on available experimental data, the maximum tractive force of a pneumatic tire on hard surfaces is usually reached somewhere between 15 and 20% slip. Any further increase of slip beyond that results in an unstable condition, with the tractive effort falling rapidly from the peak value $\mu_pW$ to the pure sliding value $\mu_sW$, as shown in Fig. 1.16, where $W$ is the normal load on the tire and $\mu_p$ and $\mu_s$ are the peak and sliding values of the coefficient of road adhesion, respectively.

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**Fig. 1.16** Variation of tractive effort with longitudinal slip of a tire.