WHEEL LOCK CONTROL STATE-OF-THE-ART

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The ability to quickly stop a vehicle under varying load and road conditions without loss of directional control obviously is important to the vehicle operator. Over the years, many improvements in braking systems have been made, but until recently, maintaining the right brake pressure for the prevailing driving and load conditions depended entirely on the skill of the driver. Now that has been changed by the development of wheel lock control systems which automatically reduce brake pressure if an impending wheel lock-up is detected. The systems modulate the brake pressure as long as the driver demands excessive brake torques. This allows more controllable and stable stops with various load and road conditions. This paper describes the current systems for preventing continuous wheel lock-up during vehicle braking. Major emphasis is placed on the wheel lock control system operation. Included is a discussion of the interaction of the wheel lock control system and the vehicle parameters to provide improved vehicle stability and control during braking maneuvers.

The ability to quickly stop a vehicle under varying load and road conditions without loss of directional control obviously is important to the vehicle operator. Over the years, significant improvements in roads, tires and braking systems have helped the vehicle operator retain directional stability during braking maneuvers (1,2). One of the more recent driver aids which have been introduced on vehicles are wheel lock control systems -- often referred to as anti-lock systems.

Although wheel lock control systems have been implemented in a variety of configurations, a basic objective of the systems has been to prevent continuous wheel lock-up on a controlled axle or wheel. The wheel lock control system continuously monitors the controlled wheel's speed. In many braking maneuvers the system never needs to control the wheel, however, if an impending wheel lock-up is detected the brake pressure is reduced. The pressure decreases until the wheel is not locked or tending to lock, at which time the brake pressure is allowed to return to the driver demand pressure unless another impending wheel lock-up is detected. If the driver demand pressure creates excessive brake torque for the the road and load conditions the system modulates the brake pressure until a low vehicle speed is reached, typically somewhat below 10 MPH (16 km/h). Through the reduction of the brake pressure, the wheel lock control system prevents continuous wheel lock-ups while allowing the controlled wheel to contribute braking and lateral stabilizing forces to the vehicle (3,4). As will later be discussed, there is a necessary compromise between the braking and lateral forces because of their natural characteristics.

The purpose of this paper is to review how a wheel lock control system operates and discuss how this system aids the vehicle operator during a braking maneuver.

The following sections outline the forces acting on a vehicle during braking and the operation of the wheel lock control system. Also included is a description of the wheel lock control system components and a brief discussion of the more complex parameters which influence a vehicle during a braking maneuver.

Primary Braking Forces

Before the operation of wheel lock control systems can be described, the primary forces acting on a vehicle during a braking maneuver must be discussed. The interaction of these forces determine the path of a vehicle during a braking effort. The effect of the primary braking forces generated by a wheel on vehicle stability and control is related to the location of the wheel in the vehicle configuration. While braking a typical two axle vehicle on a uniform road surface, locking the front wheels and not locking the rear wheels severly reduces the directional controllability of the vehicle, yet it travels in a straight path. If the rear wheels are allowed to lock and the front wheels are not locked the driver will typically be unable to prevent the vehicle from rotating. In articulated heavy-duty vehicles, locking of certain wheels can cause jackknifing.

The primary forces acting on a vehicle during a braking effort occur at each road-tire interface. Other forces such as wind loading and rolling friction are negligible during most braking maneuvers. The forces at this interface are typically defined as the tire normal force, the tire braking force, and the tire lateral force. These three forces are depicted in Figure 1.

The tire normal force is a reaction to the vehicle weight distribution, dynamically varying during a braking maneuver. The tire braking force is a reaction to the braking torque on the wheel. The lateral tire force is a reaction to any lateral motion of the vehicle. These three forces interact with each other at each road-tire interface. As one can readily observe the forces acting on the total vehicle are quite complex.

Tire braking force characteristics are commonly expressed as a ratio with the tire normal force. The ratio is referred to as μ, as defined below:

$$\mu = \frac{\text{Tire Braking Force}}{\text{Tire Normal Force}} \qquad (1)$$

This ratio is typically expressed as a function of tire slip as defined below:

$$\%\ \text{Tire Slip} = \left(1 - \frac{\text{Wheel Velocity}}{\text{Vehicle Velocity}}\right) \times 100\% \qquad (2)$$

A free-rolling wheel would be operating at 0% slip while a locked wheel would be operating at 100% slip.

A typical relationship between the tire slip and μ is shown in Figure 2. These curves are derived from experimental road test data and vary considerably with a variety of parameters (5). One of these variables is the road-tire interface surface. Figure 3 illustrates typical μ characteristics on various surfaces.

Tire lateral force can also be described as a function of wheel slip. Figure 4 shows potential tire lateral force as a ratio of tire normal force superimposed on a μ-slip curve (5). An analysis of Figure 4 shows that there is a reduction in lateral force whenever the wheel is braked. Obviously, a free-rolling wheel, 0% tire slip, gives maximum lateral force but results in no braking force. Locking the wheel, 100% tire slip, provides a great deal of braking force, but the lateral force is greatly reduced. As such, some compromise between braking and lateral force must be made during a braking maneuver.

What we have just analyzed are the forces generated at one tire-road interface. Figure 5 illustrates the forces acting in the yaw plane that determine the directional stability of a four-wheel vehicle. The vehicle is braking on a split coefficient surface; one side of the vehicle has tires on a dry asphalt surface (high μ) and the other tires on ice (low μ). This surface is rather severe as it exhibits somewhat of a limit case in vehicle stability during braking. The driver wants to stop the vehicle in an acceptable distance while maintaining directional control and stability. If excessive tire braking force in reaction to driver braking is generated, the vehicle may require a steering correction. If the additional force generated by the steerable tires is insufficient, the vehicle will rotate. After this occurs, the driver may find it very difficult to regain control of the vehicle.

The next section of the paper will describe wheel lock operation and how it aids the driver in maintaining directional control.

Wheel Lock Control System Operation

As previously mentioned, the basic objective of a wheel lock control system is to prevent continuous wheel lock-up on a controlled wheel. There have been a variety of implementations which attempt to perform this function (3,4). All of the systems monitor the controlled wheel's speed. In many braking maneuvers the system never needs to control the wheel, however, if an impending wheel lock-up is detected, the brake pressure is reduced. The pressure decreases until the wheel is not locked or tending to lock, at which time the brake pressure is allowed to return to the driver demand pressure unless another impending wheel lock-up is detected. If the driver continues to create excessive brake torque for the road and load conditions the system modulates the brake pressure until a low vehicle speed is reached, typically somewhat below 10 MPH (16 km/h).

The operation of a simplified wheel lock control system can be graphically described. In Figure 6 normalized road torque and brake torque are plotted as a function of tire slip. The road torque is related to the braking force that the given tire-road interface can generate at various tire slip levels. It should be noted that at 100% slip the road torque and brake torque are equal.

During typical braking manuevers low brake pressures and brake torques are generated. The brake torque slightly exceeds the road torque, decelerating the wheel to a low tire slip value. With this brake pressure input, the driver has defined a vehicle deceleration level. The vehicle deceleration is slightly greater than the wheel deceleration at these small slip levels. If a higher vehicle deceleration level is demanded by the driver he may increase the brake pressure beyond Point A on the brake torque curve. After this point the brake torque greatly exceeds the road torque, forcing the wheel to decelerate faster than the vehicle. As the brake torque approaches Point B, the wheel lock control system recognizes a high wheel deceleration and reduces the brake pressure. The brake torque decreases until it is equaled by the road torque (Point C) at which time the wheel acceleration is zero and maximum slip has occurred. As the wheel accelerates between Points C and D the wheel lock control system will allow the brake pressure to approach the driver demand pressure. If the driver continues to demand excessive brake torque the system will modulate the torque between Points A, B, C and D until a low vehicle speed is reached.

Figure 7 depicts the time domain operation of the simplified wheel lock control system. The figure shows vehicle speed, wheel speed and brake pressure during a full brake effort stop. The first brake pressure modulation cycle relates points A, B, C and D shown in Figure 6 to the vehicle and wheel speeds.

One will note that the wheel lock control system attempts to keep the wheel at low tire slip levels, approximately 10% to 30% tire slip. Relating this to lateral force (Figure 4), one can observe that if a compromise between the tire lateral force and tire braking is made, at these tire-slip levels, a large percentage of the two forces can be retained. As such, the directional control and stability gained with a wheel lock control system is related to the control system operation.

Wheel Lock Control System Components

The wheel lock control systems typically include three major components: brake pressure modulator, electronic control module and the wheel speed sensor. The brake pressure modulator normally transmits the driver demand pressure to the brake actuation mechanism located at the wheels. The modulator reduces the brake pressure when a brake release signal is supplied. The rate at which the brake pressure is reduced and reapplied is usually controlled by the modulator.

The wheel speed sensor is typically a variable reluctance magnetic pick-up with a frequency output that is proportional to the rotational speed of the wheel. The sensor may be positioned in the transmission, differential, axle or brake assembly where it can detect a rotating member associated with the wheel.

The electronic control module continuously monitors the wheel speed sensor output, using the frequency information to calculate wheel speed. The speed is typically differentiated to determine wheel deceleration. These two variables, speed and deceleration, are then used to determine when a wheel lock-up is impending. If an impending lock-up is detected, the control module supplies current to the brake pressure modulator which causes the brake pressure to be reduced. A more detailed discussion of wheel lock control system operation is available from several sources (6,7).

The electronic control module typically contains circuitry devoted to checking the major components and interconnections in the system. When a failure is detected by the self-check circuitry, the control module becomes disabled and cannot generate a brake release signal. This allows manual application and release of the brake pressure. Generally, a warning signal is generated by the control module indicating to the driver that the wheel lock control system is inoperative.

Vehicle Parameter Influence

Up to this point, we have reviewed the operation of wheel lock control systems as an aid to the driver in maintaining vehicle control. There are a number of vehicle parameters which influence the operation of the wheel lock control system.

Vehicle load distribution can strongly influence the behavior of a vehicle during a braking maneuver. During high deceleration stops, a large percentage of the static weight on the rear axle of a vehicle may be dynamically transferred to the front axle. In particularly severe cases, the vehicle operator may experience a great deal of difficulty in maintaining vehicle control even with a wheel lock control system.

Brake sizing and balance for a vehicle is another vehicle design consideration. Overly aggressive or unbalanced brakes may be difficult for a driver to operate, while undersized brakes may not stop the vehicle in a satisfactory distance.

Tire characteristics significantly influence the behavior of a vehicle during a braking maneuver since the major forces acting on the vehicle are generated at the road-tire interface. We have observed some typical road-tire interface characteristics and noted that they were a function of the road surface. On a given surface, the characteristics are a function of several variables including normal force, vehicle velocity and temperature. All of these variables contribute directly to vehicle stability during a braking manuever.

Summary

A wheel lock control system is designed to prevent continuous wheel lock-up of a controlled wheel. The wheel lock control system continuously monitors the controlled wheel's speed. If an impending wheel lock-up is detected, the brake pressure to the wheel is reduced. The pressure decreases until the impending lock-up condition is removed, then the pressure is allowed to approach the driver demand pressure. If the driver continues to demand excessive brake pressure for the road and load conditions, the wheel lock control system will modulate the brake pressure until a low vehicle speed is reached.

As the wheel lock control system prevents continuous wheel lock-up, the system allows the vehicle operator to better utilize the available lateral forces at the road-tire interface. As such, the wheel lock control system is a driver aid that allows the vehicle operator to retain directional stability and braking effort under many road and load conditions.

References

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Figure 1. Road-tire interface forces.

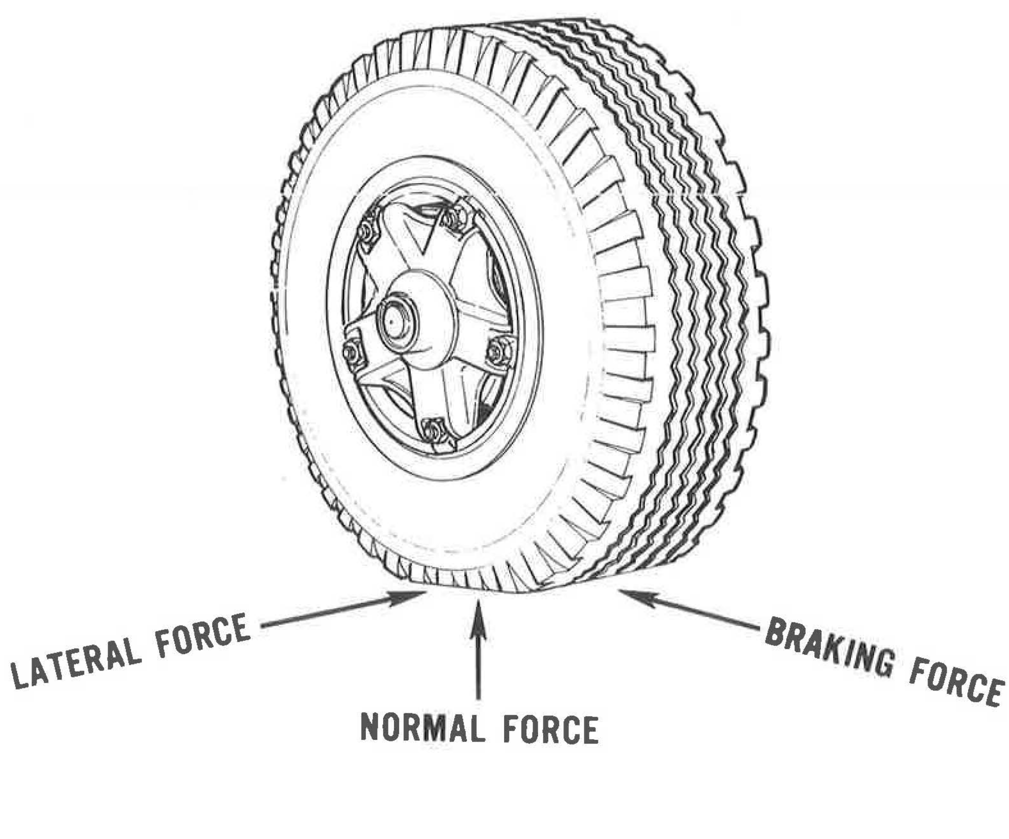

Figure 2. Tire braking force characteristics.

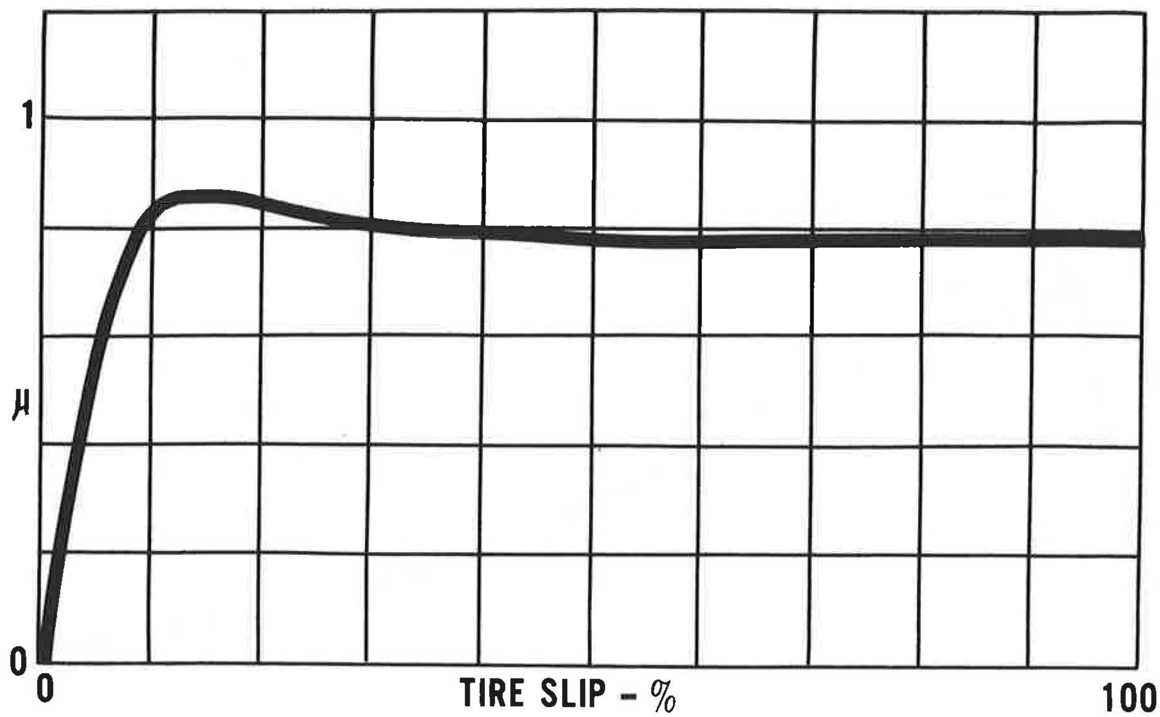

Figure 3. Surface variation of tire braking force characteristics.

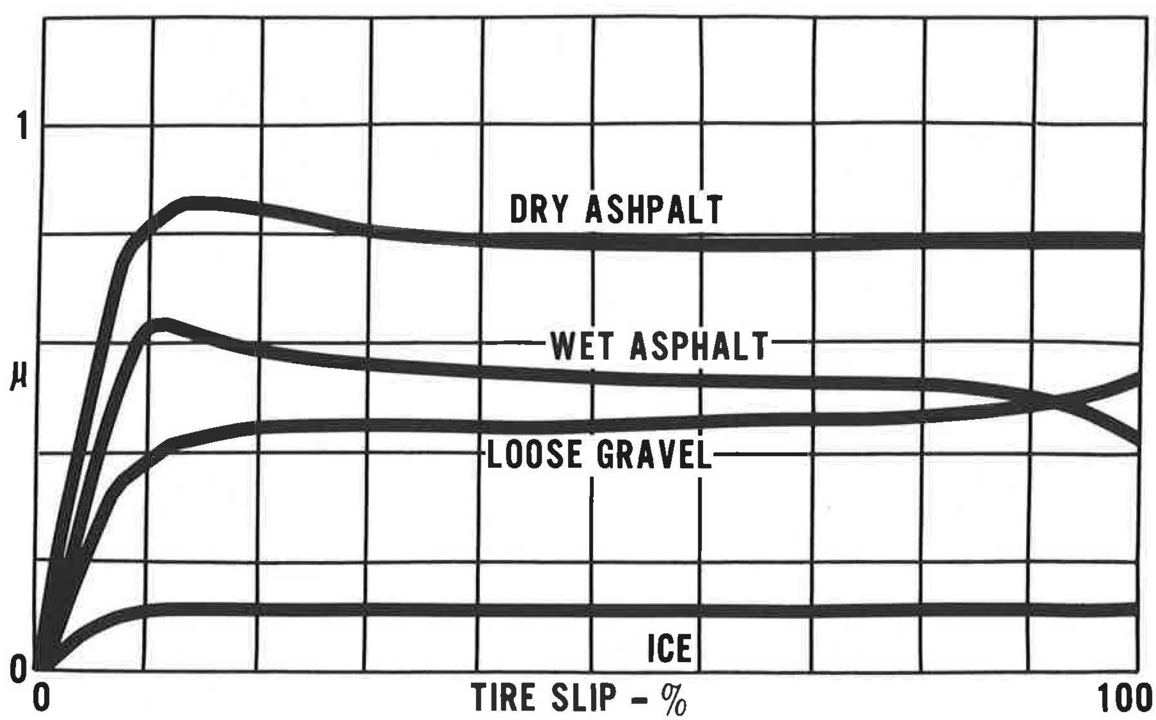

Figure 4. Tire lateral and braking force characteristics.

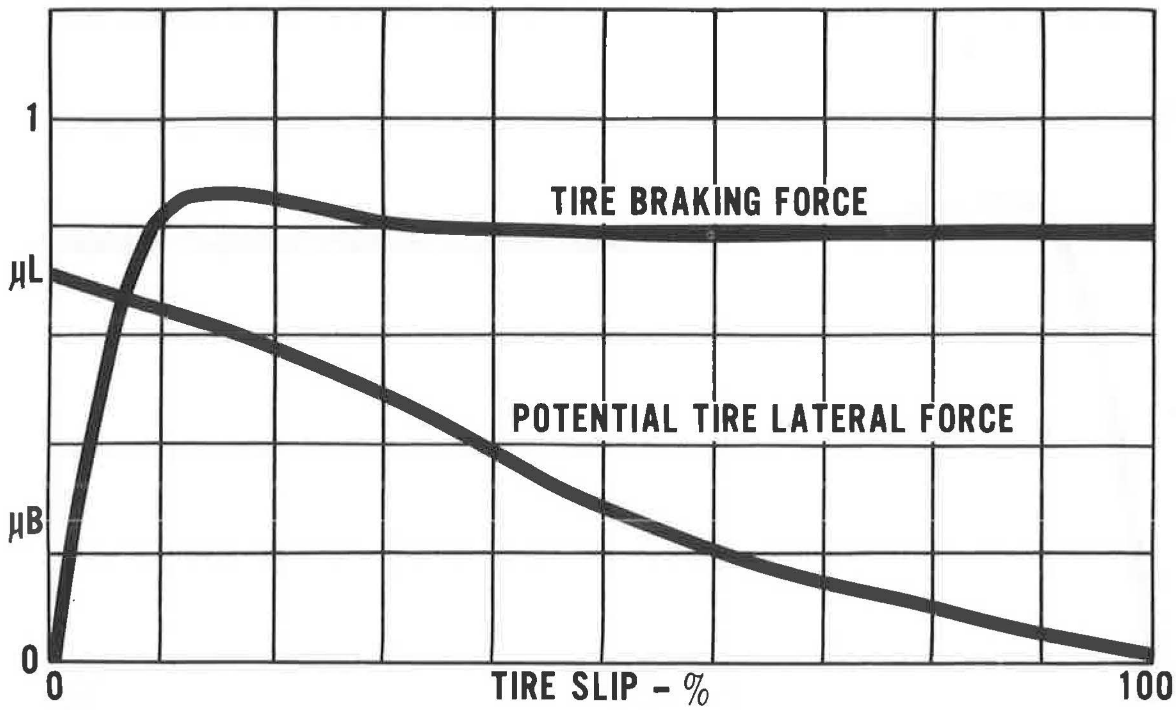

Figure 5. Split coefficient braking forces.

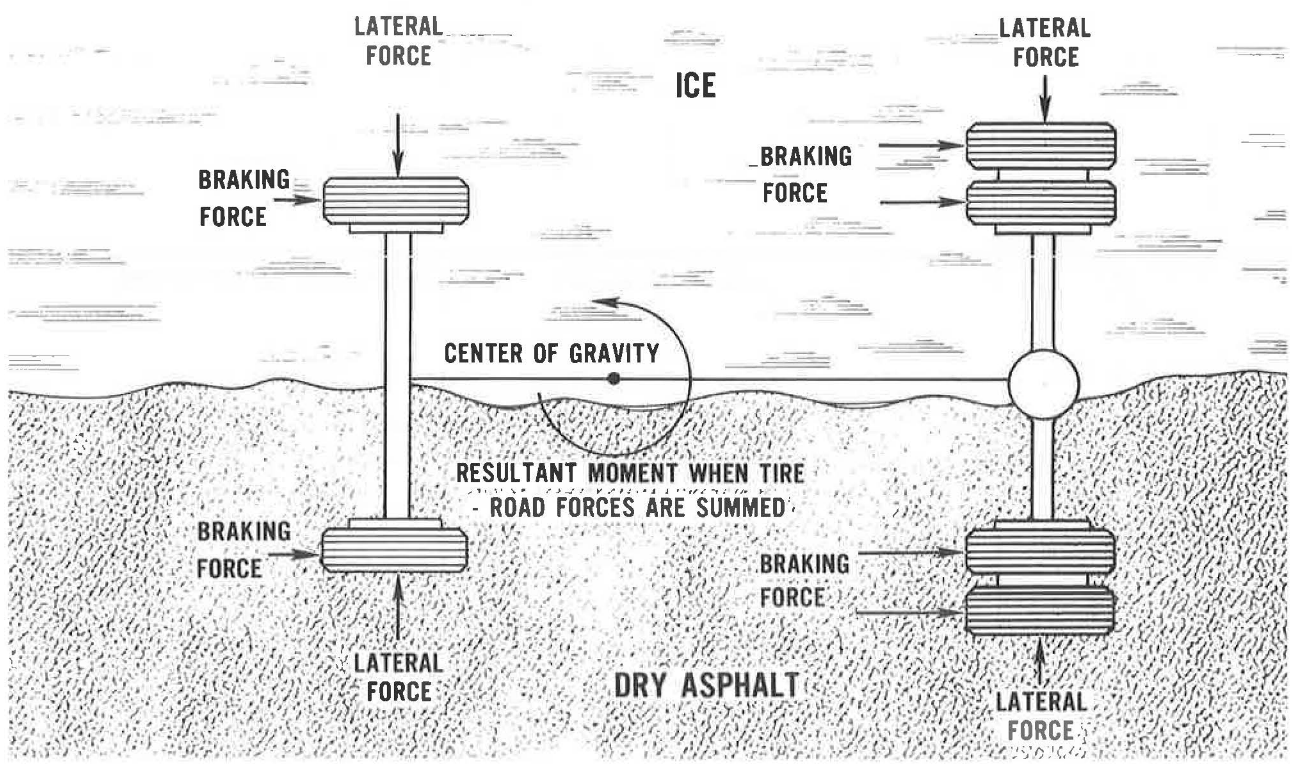

Figure 6. Wheel lock brake torque modulation.

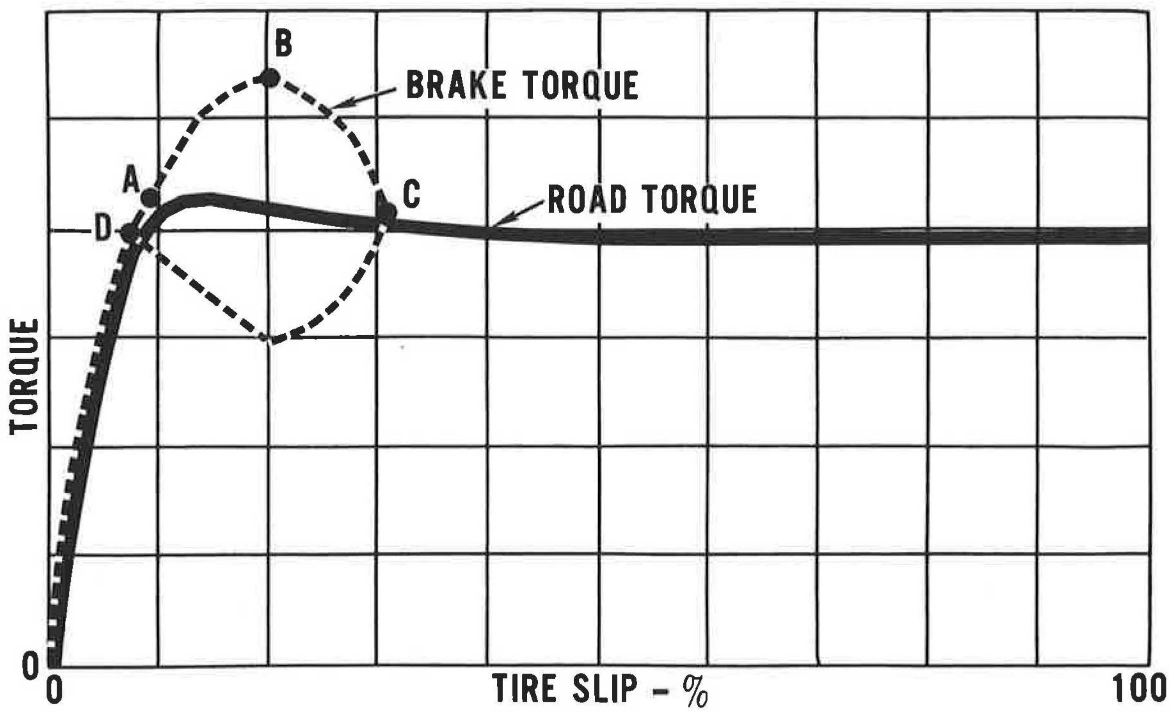

Figure 7. Full brake pressure wheel lock control stop.