BRAKES AND SKID RESISTANCE

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This paper gives a general review of passenger car antilock braking systems, describes their manner of operation, and discusses their effects on vehicle braking performance and stability. Particular emphasis is placed on the influence of antilock brakes on vehicle stability and stopping performance in straight-ahead braking and cornering situations over a broad range of speeds and pavement conditions. Antilock system options and the relative merits of two- and four-wheel systems are discussed along with possible future prospects.

•THE forces that govern the motion of the automobile over the road are generated at the tire contact patches. The magnitudes of these forces are functions of road surface condition, vehicle weight, and input variables from the three potential magnitudes of forces at the tire-road interface and are determined by a traction coefficient, or skid number, μ (Fig. 1) (1).

Several types of braking devices, intended to improve braking performance when traction coefficients are low, have been proposed and tested during the past 20 years. These devices have, in general, been designed to adjust the front-to-rear or side-to-side braking loads, as required, for nonuniform pavement conditions or varied vehicle load distribution. Devices such as load-sensing hydraulic proportioning valves and brake torque-limiting schemes have been tried with varying degrees of success.

Foremost among the more recent developments is the antiskid or antilock brake system. This paper reviews existing antilock systems, their manner of operation, and their effects on vehicle performance.

BASIS OF OPERATION

The antilock brake system is designed to prevent wheel lock and the consequent possible loss of control and to make the most efficient use of the available traction to stop the vehicle. One example is the Ford Sure-Track system (Fig. 2). This package consists of a drive line speed sensor, a solid-state control module, and a vacuum-powered hydraulic actuator. Other available systems on U.S. passenger cars are similar, with variations in the number of axles or wheels being controlled. The functions of these systems are to detect impending wheel lock through information supplied by the speed sensor to the control module and to modulate braking line pressure to prevent wheel lock by means of the hydraulic actuator responding to commands from the control module. The resulting modulation is similar to the pumping action that a skilled driver would execute manually in a panic braking situation.

The potential of these systems is clarified by examining the characteristic tire torque capacity versus wheel slip (or μ-slip) curve (Fig. 3) (2). The braking capacity of a tire on some types of surfaces is less at 100 percent slip, or wheel lock, than at some lower value of slip. If the brakes are applied and released cyclically in a manner that will maintain braking torque at or near its maximum and wheel slip at less than 100 percent, lateral stability is more likely to be maintained. In addition, with a higher average braking torque, stopping distance can be reduced to less than the locked-wheel stopping distance.

Figure 4 (2) shows the capacity of a tire to resist side loads at various values of wheel slip. The advantage of keeping μ-slip at a low value is clear. In the locked-wheel condition, the ability to react to side loads has vanished. The effect of locked

Figure 1. Concept of traction envelope.

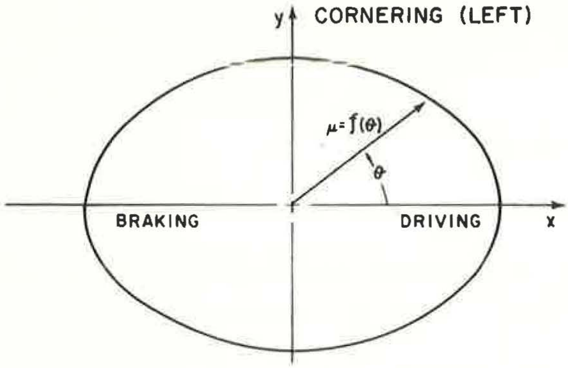


Figure 2. Sure-Track system components.

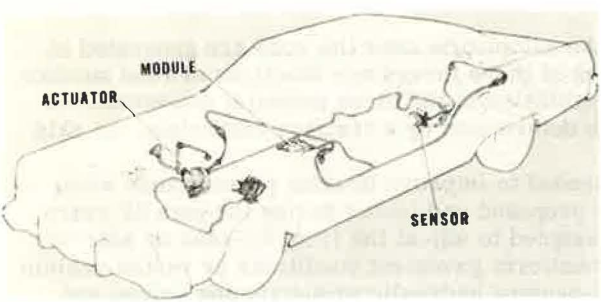


Figure 3. Representative tire-brake force.

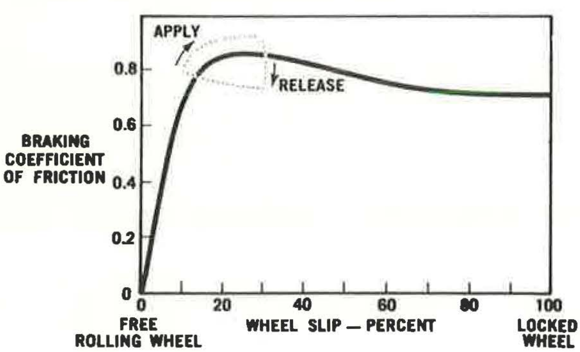
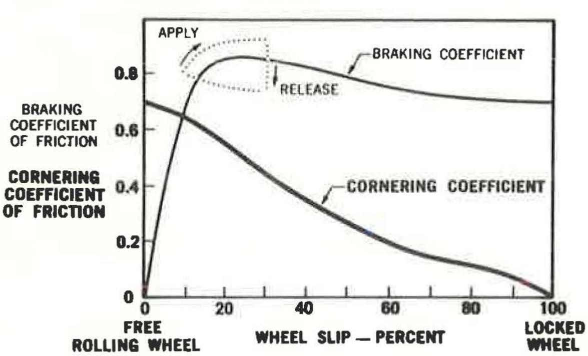


Figure 4. Representative tire-brake and cornering forces.



wheels is different for front and rear wheels. Locked front wheels cannot develop cornering traction. This means that the car will not respond to steering wheel movements and will tend to "mush" in a straight-ahead path of travel, unable to negotiate a curve in the road. On the other hand, locked rear wheels during a cornering maneuver can result in rear-end breakaway with the car tending to move either into an oncoming traffic lane or off the roadway, depending on the initial direction of travel. These critical consequences are the primary justification for antilock brake systems. The reduction of stopping distance is an additional benefit to be realized on certain types of pavement surfaces but not on others, as will be seen.

PERFORMANCE VARIABLES

The performance of an antilock system varies with pavement conditions and also with the speed of the vehicle. Figure 5 (2) shows steady speed μ-slip curves for ice at 20 and 30 mph. The 30-mph curve shows a peak to locked torque ratio greater than one, and it appears that some improvement in stopping distance might be expected with an antilock system. The 20-mph curve, however, shows maximum friction with locked wheels and therefore no prospect of shortened stopping distance. Ice-covered pavements in general show a wide variation in μ-slip characteristics with speed and also with ice temperature. The presence of snow over ice further confounds the consistency of stopping performance on ice. As a practical matter, characteristics of tire-pavement surface combinations for ice and other materials vary enough that, from the standpoint of stopping distance, the performance of the antilock system can be better than, the same as, or less than the performance of the vehicle with locked wheels.

Antilock systems generally perform best on surfaces that exhibit a high peak to locked wheel torque ratio, as on wet asphaltic concrete (Fig. 6) (3).

When braking torque is maximum at the locked-wheel condition, stopping distance will be longer with the antilock system because it will prevent the wheels from locking. In the absence of a distinct peak at low slip in the μ-slip characteristic curve, no improvement over locked-wheel stopping distance can be expected, and some deterioration of performance is likely.

Table 1 (4) shows that four-wheel antilock performance, as compared to locked wheels, can effect as much as 41 percent shortening of stopping distance on wet Jennite or can appreciably lengthen the stopping distance, as on gravel. The performance on dry concrete was not impressive with a 3.8 percent increase, but it improved to 11.5 percent shortening on wet concrete. The 11 percent improvement on snow and ice is an average for various environmental conditions. Gravel is one of those surfaces where peak friction occurs at 100 percent slip; therefore, the antilock stopping distance is greater than that for locked wheels.

A common condition on winter highways is a patch or narrow strip of ice or snow adjacent to a strip of dry pavement. At a speed of 25 mph and for surface coefficients of 0.85 on the right and 0.25 on the left, split-friction performance is as follows (5):

System	Yaw Angle (deg)
Rear-wheel antilock	
Minimum	5
Maximum	30
Average	17.8
Conventional (out of control, all stops)	>90

These data were observed on a vehicle with a rear-wheel antilock system. In executing the stops, the front wheels were locked while the antilock system prevented rear-wheel lock. With the right-side wheels on a 0.85-μ surface and the left-side wheels on a 0.25-μ surface, the vehicle deviated an average of about 18 deg from its intended path during panic stops, compared to complete loss of control with antilock system turned off.

Figures 7 and 8 (5) show the results of similar tests on pavements with uniform coefficients. On wet asphalt from 60 mph with the rear-wheel antilock system operating,

Figure 5. Characteristic tire-brake force (ice at 30 F).

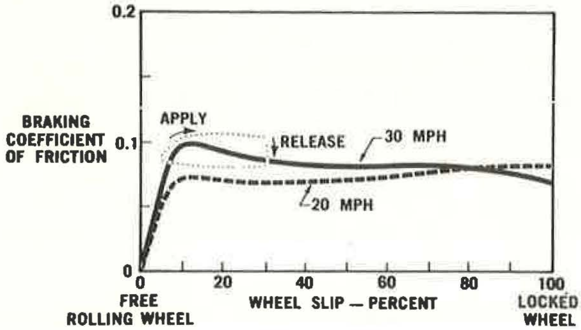


Figure 6. Characteristic tire-brake force (asphaltic concrete covered with 0.04 in. of water).

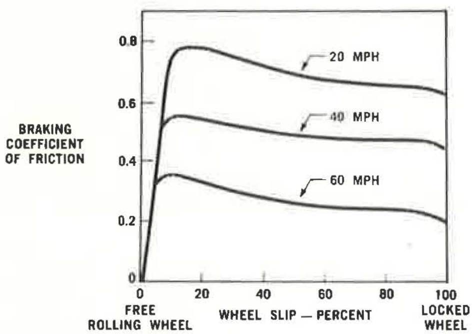
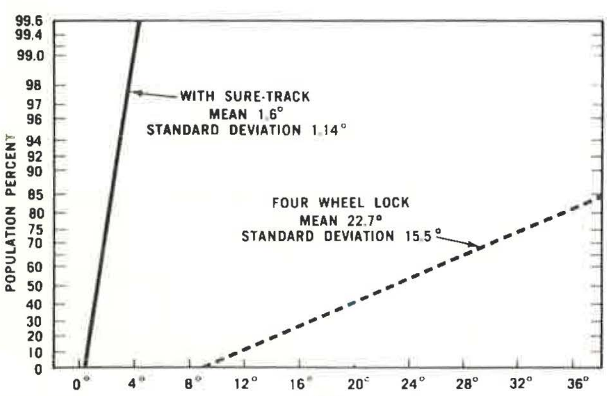


Table 1. Performance of four-wheel antilock brake system.

Speed (mph)	Condition	Stopping Distance (ft) Locked Wheels	Stopping Distance (ft) Four-Wheel Antilock	Percentage of Improvement
60	Dry concrete	159	165	-3.8
60	Wet concrete	200	177	+11.5
30	Gravel	52	65	-25.0
45	Wet Jennite	315	186	+41.0
45	Snow and ice	255	227	+11.0

Figure 7. Improved yaw control (stopping at 60 mph on water-covered asphalt).



the mean yaw angle was 1.6 deg compared to 22.7 deg for the same vehicle with the antilock system inoperative and all four wheels locked. On a hydrolube surface at 20 mph with 0.05 μ (Fig. 8), mean yaw angle was 6.8 deg with antilock and 59 deg without. On an overall basis the antilock system provides appreciable yaw reduction.

Judging from the μ-slip curves, studded snow tires are not likely to shorten antilock stopping distance on ice because there is no peak at low slip (Fig. 9) (3). Plain snow tires exhibit a slight peak, and brake modulation at low slip could theoretically effect a reduction in stopping distance. Snow and studded snow tires have not yet been adequately investigated as to their effects on antilock performance, however, and conclusions are difficult to reach. In any case, the antilock system would tend to prevent loss of control.

SYSTEM OPTIONS

Antilock systems now available to the public are similar in the basic hardware employed. A choice exists, however, as to which wheel combinations are selected for control. The ultimate system might have individual control on each of the four wheels. Figure 10 shows a system with independent control on each of the front wheels and independent wheel speed sensing on the rear wheels, with the rear wheels sharing a common actuator. In this system, each front wheel's braking load is determined by the coefficient of friction at each tire-pavement interface. In the rear, however, both brakes are modulated alike. When wheels are paired in this manner, a logic circuit may be built into the control module to select the wheel that is on the surface having the lowest coefficient as the control feedback. In this way, the braking at the rear wheels is governed by the wheel that is nearest to skidding.

The four-wheel system versus the two-wheel system is a subject that could be debated at length. The most obvious advantage of four-wheel control is the ability to steer the vehicle during panic braking. The importance of good directional control as compared to maintaining a straight stopping path is substantiated in accident studies that show that lack of directional control is a more frequently observed pre-impact behavior than lack of stopping ability (6). Against the advantage of directional control must be weighed the increased cost, complexity, and reduced reliability of the four-wheel system.

From the standpoint of stopping ability, it would appear that the four-wheel system should perform better than the two-wheel system, particularly because the two front wheels normally carry the largest share of the braking load, and on some surfaces this is the case. In other instances, however, the expected improvement is not realized. On gravel, for example, locked front wheels may plow aside the looser material and allow the rear-wheel system to operate on a firmer surface than would be possible with the front wheels rotating. On wet pavements, the locked front wheel has a more effective wiping action than the rotating wheel so that the rear wheel, following in its track, may be operating on a thinner water film or even on virtually dry pavement. The locked front wheel thus can contribute to the efficiency of the two-wheel system in some instances.

FUTURE PROSPECTS

Antilock systems will undoubtedly undergo further refinement. Improvements probably can be made in both the control systems and the conventional brake components that they control. Reduction of system response time and use of continuous rather than cyclic or on-off control appear to be important goals for the future, both in passenger cars and in trucks, where the application can be much more complex.

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Figure 8. Improved yaw control (stopping at 20 mph on hydrolube surface).

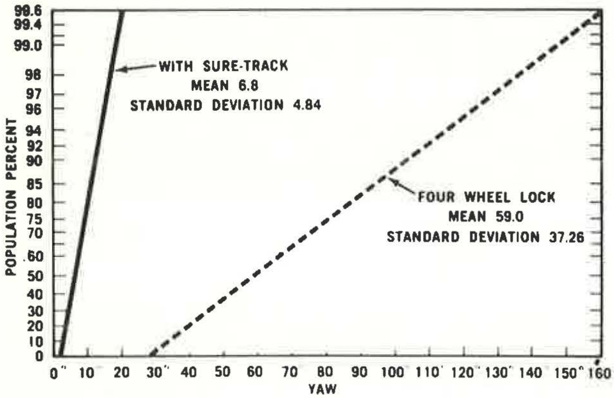


Figure 9. Characteristic tire-brake force (ice at 25 F and speed of 20 mph).

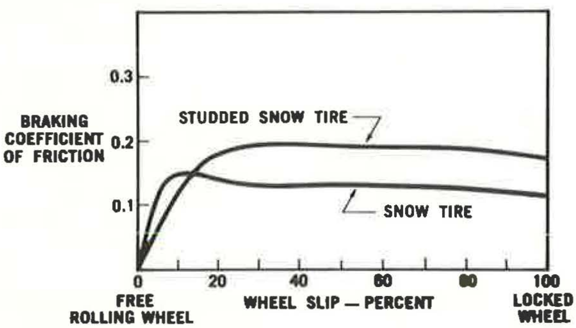
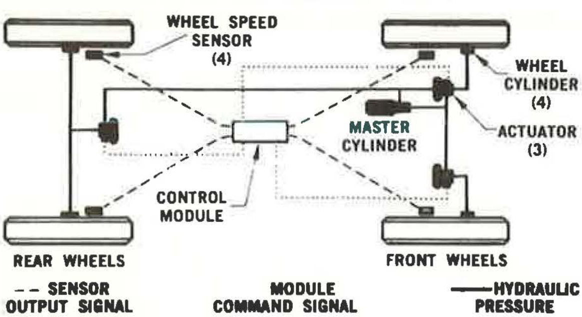


Figure 10. Elements of antilock brake system.



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