the driver, the vehicle, and the driving environment. Researchers were striving to accomplish this goal as early as 1924, and yet it has not been fully realized $5\frac{1}{2}$ decades later. At times, it seems to be becoming more elusive than ever because of the improved maneuverability of the automobile and increased travel, which causes accelerated pavement wear.

Much of the highway research in these past decades has been directed to seeking an incremental solution to each of the three contributing areas—the driver, the vehicle, and the roadway—rather than to mounting a significant interdisciplinary effort in all areas. Two of these areas are in the public domain and are sensitive to the needs and desires of the public; the third is in the private area of automobile and tire manufacturers who, although subject to state and federal regulations, are confronted with a problem whose solution will most likely increase the cost of their products and place limitations on their designs.

The most concerted effort in the roadway area has been the measurement of skid resistance and the development of corrective measures. Driver education has taken an independent and separate approach. Only recently have educators made an effort to include in driver programs the opportunity for the student to receive skidding experience during driver training. Automobile manufacturers, while being concerned with safety features such as handling characteristics and braking performance, have relied heavily on the tire manufacturer for improving the tire-pavement interaction. In spite of the piecemeal incremental approach to research, great technological strides have occurred in all areas. The time has now come for us to systematically optimize the relation of the driver and the machine with the driving environment. Now is the time for an expanded effort in bringing together the currently available knowledge into a disciplinary approach to seeking acceptable solutions to the goal of providing wet-weather, skid-safe travel.

A number of milestones have occurred during the years in an effort to reach this goal. The First International Skid Prevention Conference held in September 1958, which included a preconference field correlation study, emphasized the need for greater standardization of field measuring equipment. An outgrowth of that conference was the formation of the ASTM Committee on Skid Resistance. The 1962 correlation study near Tappahannock, Virginia, was organized to compare the latest designs in test equipment in an effort to afford an opportunity for greater standardization. The 1967 Florida Skid Correlation Study was an attempt to evaluate the degree of standardization achieved by several skid trailers constructed in accordance with the newly developed ASTM Test for Skid Resistance of Pavements Using a Two-Wheel Trailer. In 1968 a study was conducted at Wallops Island, Virginia. In 1972, the Pennsylvania State University conducted a locked-wheel skid trailer correlation and calibration study for the National Cooperative Highway Research Program. Although I recognize that the second international conference was directed to subjects other than skid trailers specifically, my experience has been that we are now probably able to correlate skid trailers largely because of the FHWA-sponsored field test and evaluation centers. These centers provide a sound basis for calibrating skid trailers and should provide a greater correlation nationwide for these instruments.

But the second international conference dwelled not on one small aspect of creating skid-safe travel during wet weather but on all elements of the problem. The conference objectives, which emphasized implementation of research findings, were to

1. Present an overview of current knowledge,
2. Demonstrate how this knowledge can be applied to improve safety, and
3. Determine what further steps must be taken to learn how existing knowledge can be applied or what further research is needed.

Report of Subcommittee on Tires, Vehicles, and Vehicle Components

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IMPLEMENTATION OF KNOWLEDGE

Opportunities for implementing improvements take place almost automatically in competitive industries such as vehicle and tire manufacturers. Therefore, there has been no formal implementation program of those things learned in the 19 years since the First International Skid Prevention Conference. As improvements became available, they were adopted immediately. Since the first international conference, the tire industry has just about doubled the wet coefficient of tires on slippery roads and at the same time doubled tire life.

One matter, however, that the tire manufacturers could not deal with and that needs immediate attention is the matter of laws governing minimum tread depth.

In a panel discussion during the second international conference, John R. Treat of Indiana University estimated that a 28 percent increase in wet coefficient of friction would decrease skidding accidents by 50 percent. An increase of this magnitude could be achieved, for the vehicles most likely to skid, by replacing bald tires with tires having at least a groove depth of 1.6 mm ($\frac{2}{32}$ in). Minimum tread-depth laws already exist in about 35 states and many other countries. Such laws are being effectively enforced in Germany and the United Kingdom. During the conference, a representative from Virginia indicated that minimum tread-depth laws can be effectively enforced by a required vehicle-inspection program every 6 months.

Skidding Problem

1. Skidding is not clearly defined and tends to mean different things to different people. It can probably best be defined as the inability of a driver to exercise control because of poor road grip.

2. The skidding problem involves a system: driver, vehicle, and road. Coordination of activities related to all three elements in the system is essential if improvement is to be made, since interaction takes place among the three elements.

Vehicles

1. Vehicles, and their component parts, are highly variable. Their performance relative to skidding is affected not only by design but also by deterioration with age, normal wear, and the level of maintenance.

2. The four tires on a passenger automobile are in themselves different, and in many cases the left tires will operate on a different surface than the right tires, particularly when the surface is wet.

3. The trend toward lighter automobiles will increase the effect of wind and aerodynamic lift.

4. Automobile maneuver is just as important in skid accidents, or skid-accident avoidance, as deceleration or stopping capability.

5. The skid number of a tire on a given surface does not necessarily reflect either its cornering capability on that surface or its performance during combined cornering and braking. Therefore, the skid number measurement does not necessarily relate well to maneuvering capability of the vehicle.

6. Understeer characteristics can be designed into the vehicle geometry. Understeer is desirable because it tends to resist rotation of the vehicle about its own vertical axis.

7. Vehicles should be, and are being, designed to prevent rear wheels from locking. On passenger automobiles this is currently done by brake proportioning and could also be done with antilock braking systems.

8. A nonrotating (sliding) tire provides no directional control at all. To maintain vehicle maneuverability requires the prevention of front wheel lockup. Antilock braking systems relieve the driver of difficult decision making and actions. Antilock braking system technology is currently available, but its cost-effectiveness is questionable, particularly for passenger automobiles.

9. Vehicles encounter friction coefficients that vary from 0.1 on icy pavements to 1.0 on dry pavements and from 0.3 to 0.6 on wet pavements. A sudden change in tire-road friction coefficient creates a difficult problem for the driver. Almost nothing can be done to the vehicle or the tire to overcome this problem because it is essentially related to the highway surface. It is particularly important that roads be constructed and maintained so that puddles of water do not accumulate. When water depth is greater than 50 mm (0.5 in), the automobile or tire can contribute little to vehicle control at cruising speeds.

10. Vehicles should be, and generally are, designed to give ample warning of impending breakaway (in cornering) and to provide means of correction through steering inputs before breakaway occurs.

11. Computer simulation of vehicle dynamics, including antilock braking systems, is possible with known technology and is an effective tool for optimizing vehicle design.

12. Banholzer (1) describes a special design of front-end geometry combined with a diagonal-split braking system that illustrates the potential of good vehicle design relative to avoidance of skid accidents in wet weather.

Brakes

1. In the United States, several manufacturers make antilock brake systems that are now used on heavy trucks (primarily because of federal safety regulations), and such systems have also been available, at extra cost, on passenger automobiles made during the last few years. Antilock braking systems are tremendously complex and therefore costly.

2. In Europe, less costly methods for preventing wheel lockup are used although no claim is made that they provide the sophisticated performance features of the antilock systems.

Measuring Equipment and Techniques

1. The towed test trailer is a good device for measuring straight-ahead tire-road coefficient of friction. Such trailers can be equipped with modern electronic instruments, which reduce the measuring-device error and improve the efficiency of repetitive testing. However, the accuracy of the test trailer is not the limiting factor in accurately measuring tire-road friction. More variation is created by the watering system than by the trailer.

2. Much more sophisticated mobile tire testers have been constructed and are in use for detailed tire studies. These test devices can measure tires at various slip percentages, slip angles, and camber angles. Therefore, the test equipment technology is already available for application in studies of passenger automobile tires.

3. Devices to measure truck tire traction have only recently been constructed, and not much is known about their accuracy or efficiency. Most of those in existence are large trailers capable of handling the heavy loads involved with truck tires.

4. Indoor laboratory machines are available for testing tire coefficients of friction, but their use is limited because not enough is known about the correlation of test results obtained by the machines and on the road. One such machine in the United States provides a flat test surface, but there is some question about the turbulence of the water encountered by the tire and also about the surface material, which is not like that on ordinary road surfaces. Laboratory machines that use the interior surface of a test drum are available in Europe and Japan. Such machines can provide good control of water depth, and the water is not turbulent at the time tire measurements are made. At least one such machine is capable of using sections of real road-surfacing material as a test surface. These machines are promising although the tire is still in a somewhat unnatural situation in that it is running on a curved rather than a flat surface. Some comparative tire testing may now be done with indoor laboratory machines, but these machines need more work to improve their usefulness.

Tires

1. Internal tire construction has no significant effect on sliding or peak coefficient of friction. However, radial-tire body construction permits open tread designs that do increase wet coefficients of friction significantly. Radial-tire body construction also provides substantially higher cornering force at normally encountered slip angles, but does so because of elastic tire properties rather than tire traction.

2. The wet-traction performance of tire tread compounds is primarily determined by the kind of rubber used in the compound. High hysteresis (low resilience)

types are best for wet traction but correspondingly poor for rolling resistance and wear. Carbon black and oil in the tire tread compound are other materials having some influence. Tire tread compound for wet traction might be improved, but only at the expense of some other important property such as wear, rolling resistance, dry traction, and crack resistance. Tire tread compounds are currently at a near optimal balance.

3. Void content in the tire tread is the primary factor in providing wet traction, although increasing void content beyond a certain point is not effective. (Increasing the void content beyond a certain point also results in serious wear loss and handling deficiencies on dry pavement.) Voids in pavement texture (macrotexture) can provide the same effect as voids in the tire tread. The more macrotexture that the surface has, the less that is needed in the tire tread.

4. Wet-traction coefficients gradually decrease (especially on low macrotexture surfaces) as treadwear increases. Such coefficients fall off sharply at tread depths of about 2 mm (slightly more than $\frac{2}{32}$ in) for both passenger automobile and truck tires.

5. The operating condition that has the greatest effect on the performance of passenger automobile tires on wet pavement is speed. Coefficients decrease as speed increases. Coefficients are also substantially reduced by relatively deep water. Variations in load and inflation have little effect on measured coefficients.

6. Peak values of braking coefficients occur at about 15 to 20 percent wheel slip. On slippery surfaces, peak values are about twice as high as slide values. Peak and slide values correlate directly.

GAPS IN KNOWLEDGE

Several conference participants commented on the need for international coordination of skid-prevention activities. The United Kingdom and the Netherlands have such coordinated programs, but in other countries, including the United States, there are no established ways to initiate such programs. A research project should develop a scheme for coordinating research and implementation of knowledge relative to the driver, vehicle, tire, and road.

Vehicles

1. Ways need to be found to motivate vehicle owners to maintain their vehicles (and components) properly.

2. Studies are needed to compare antilock braking systems with other braking systems for trucks relative to effectiveness in preventing skids.

Measurement Equipment and Techniques

1. A device is needed to accurately measure water depth of less than 1 mm (0.04 in).

2. The effect of water turbulence on measured values of coefficients should be determined so that this source of variation on test trailers can be quantified or minimized.

3. A standard method is needed for dispensing water on a test trailer. This research involves standardizing the nozzle and its orientation with respect to the tire and the road.

4. Based on appropriate research, a choice should be made between on-board and external watering for purposes of tire testing.

5. More work should be done to determine the correct water depth (or water volume) for testing. Different standards for surfaces of different macrotexture may be required. The purpose is to simulate actual conditions during a rainfall.

6. A better technique for measuring peak values of coefficient of friction should be developed, particularly as interest in antilock brake systems increases.

7. Equipment and techniques for measuring truck tire traction should be standardized.

8. Equipment and techniques for measuring cornering traction (in both the steady state and transient modes) of passenger automobile tires should be further developed and standardized.

9. Research should be done to determine whether dynamic, rather than static, calibration is needed for test trailer transducers.

Tires

1. More data are needed on tire performance over longer stretches of roads (including those with a typical amount of unevenness) to improve computer simulation of vehicle performance.

2. Data on truck tire traction are needed for vehicle simulation programs.

3. Research can be undertaken to develop methods to renew traction of worn tires.

4. A cost-effectiveness study should be made relative to the enforcement of minimum tread-depth laws in comparison with other means of increasing the tire and road coefficient of friction.

5. The development of some kind of noise (or vibration) indicator built into a tire to indicate when a 1.6-mm ($\frac{2}{32}$-in) groove depth is reached could provide an alternate method for reducing the number of bald tires in use.

Pavements

More information should be obtained on seasonal variations in pavement coefficients of friction, which are reported to be lowest in the September-October period and to increase before freezing and thawing begin.

REFERENCE

1. D. Banholzer. Design of Suspension to Prevent Pulling to One Side and Skidding During Braking, Particularly on a Surface With Differing Coefficient of Friction. TRB, Transportation Research Record 621, 1976, pp. 28-33.