A State-of-the-Art Report

The Influence of Roadway Surface Discontinuities on Safety

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This report presents the findings of the Task Group appointed by the Committee on Surface Properties-Vehicle Interaction to identify and discuss the safety implication of significant categories of surface discontinuities and document relevant literature for each category. Topics are as follows: accident data relationships; surface friction and traffic accidents; surface discontinuities and traffic accidents. roughness, holes, and bumps: roughness; potholes; curbs. pavement edges: the phenomenon; testing and analysis; summary of findings. friction variations: transverse friction; longitudinal friction variations; pavement markings; steel grid flooring; traveled surface to shoulder. water accumulations: hydroplaning and hydrodynamic drag; visibility. surface contaminants: ice and snow; earth, sand, gravel, and mud; diesel fuel. small and large vehicles: special considerations for small vehicles; special considerations for large vehicles. conclusions. biographical data.

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WASHINGTON, D.C. 1984

Transportation Research Board State-of-the Art Report

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PREFACE

It is generally recognized that discontinuities in roadway surfaces can cause problems with vehicle steering, braking, maneuvering, and response that lead to loss of control. Such discontinuities can play a significant role in the occurrence of traffic accidents and they should be considered when assessing maintenance policy, evaluating pavement safety, and planning and designing highway safety improvements. Discontinuities include deviations from the intended physical characteristics of the traveled surface that result from traffic loads, environmental effects, or other causes. In the context of this report they also include pavement edge geometry, water accumulation, and surface contaminants.

The relationship between roadway surface discontinuities and traffic safety has been a topic of discussion for many years. However, except for surface friction, literature attempting to relate discontinuities to accidents is limited. The Transportation Research Board's Committee on Surface Properties-Vehicle Interaction recognized that no comprehensive effort had ever been made to compile and discuss the various kinds of discontinuities that occur in roadway surfaces and their influence on traffic safety. Consequently, a Task Group was appointed by the Committee to compile such a document.

The objectives of the Task Group were to identify and discuss the safety implication of significant categories of surface discontinuities and document relevant literature for each category. The results of the Task Group's activity, contained in this report, will provide a useful resource for decision makers and others involved in providing and maintaining safe traveled surfaces.

The Transportation Research Board and its Committee on Surface Properties-Vehicle Interaction express their thanks to the Task Group chaired by Don L. Ivey for their significant contributions. Biographical information on the authors is contained in the appendix of the report. Special recognition is accorded Robert M. Olson, who provided editorial consultation in compiling the report.

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CHAPTER 1 Introduction

Don L. Ivey

For more than 60 years highway engineers have labored diligently to construct and maintain the U.S. highway system. These endeavors have been aimed at providing a system of highways that is safe. It should be noted that during this time the types of vehicles have changed and drivers have come to expect satisfactory highway and roadway conditions. Because of the deterioration of the aging U.S. highway system, roadway maintenance has become a major expense; unfortunately, adequate funds are not available to consistently maintain highways in the safest condition.

Safety on the highways is a function of many variables, include the condition of drivers, vehicles, weather, and the highway. The first two conditions are not in the province of this report, which is limited to a discussion of discontinuities in roadway surfaces under varying environmental conditions and their effect on highway safety.

Examples of discontinuities are holes, ice, edge drops, curbs, and changes in surface friction. These conditions are frequently unexpected by vehicle operators. The purpose of this report is to present what has been learned about discontinuities in roadway surfaces. The objective is to provide information that may prove useful to highway engineers and administrators when decisions on maintenance expenditures are required.

The TRB Committee on Surface Properties-Vehicle Interaction (A2B07) discovered that no comprehensive effort had been made to compile and discuss the various kinds of discontinuities that occur in highway surfaces. Task Group 1 has performed this task, and the results of its efforts are contained in the following chapters, which contain more than 90 references. The Task Group recognizes that it does not include all references related to this subject, but it believes that the information presented herein is responsive to the purpose and objective of its effort.

A summary of the most significant reports must begin with the work of Agg (1) in 1924 and Moyer (2) in 1934. Drive and braking traction on soil, gravel, and mud--the common road surface materials in those years--were studied. The landmark work of Kummer and Meyer (3) on tire pavement friction, and studies by Horn (4) and Gallaway et al. (5) on hydroplaning represent major contributions.

Other studies include the work on pavement edges by Klein et al. (6), Nordlin et al. (7), and Zimmer and Ivey (8). Olson et al. found that "curbs offer no safety benefit on high speed highways" (9, p. 15). Whitehurst and the National Safety Council (10) made important contributions on the effects of ice and snow on traction. Limited efforts to consolidate the highly fragmented information on this subject were made by Ivey and Griffin (11) and Klein et al. (6) in the mid-1970s.

The writers trust that their efforts will be responsive to the objectives stated earlier; that this document will be useful to practicing highway engineers in making evaluations of maintenance guidelines and priorities; and that this document will help modify current practices, as may be appropriate.

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CHAPTER 2 Accident Data Relationships

Lindsay I. Griffin III

Surface Friction and Traffic Accidents

Traffic accidents can be complex events. To assume that traffic accidents, or a given subset of traffic accidents (e.g., accidents that result from inadequate surface friction), can be accurately predicted on the basis of one antecedent condition such as skid number is wishful thinking.

Making the situation even more difficult is that accidents are rarely categorized as resulting from inadequate surface friction. Instead, some surrogate for inadequate friction must be found. The usual candidate is wet surface accidents. The tacit assumption in choosing this surrogate is that an accident that occurs on a wet surface is the result of inadequate friction. As Hegmon (1) points out, accidents that occur on wet surfaces may or may not be associated with inadequate friction. It follows that it is extremely difficult to predict wet surface accidents solely on the basis of skid number.

In a recent review of the literature on the association between wet surface accident rate and skid number, an unsatisfactory association between the two measures was demonstrated (2). In that review a simple linear regression of wet accident rate on skid number (SN_{70}) was calculated for data contained in Rizenbergs et al. (3). The resulting equation was

$$AR = 31.80 - 0.55\ SN \quad (1)$$

where AR is the wet accident rate (wet accidents per 100 million vehicle miles), and SN is the skid number (SN_{70}) predicted for a speed of 70 mph. This equation accounted for 8.7 percent of the variance in wet accident rate.

This same regression procedure was then applied to a second set of data provided by Rizenbergs et al. (4). In this case the resulting equation was

$$AR = 101.58 - 1.51\ SN \quad (2)$$

(Note that for this second data set skid numbers were recorded at 40 mph.) This second regression equation accounted for 9.6 percent of the variance in the wet accident rate.

Equation 1 was based on data from rural, four-lane, controlled-access highways. Equation 2 was based on rural, two-lane roads. The low values of 8.7 and 9.6 percent indicate that skid number alone is not extremely helpful in predicting wet weather accident rates.

It should be recognized that the frictional properties of a road surface are not inherently adequate or inadequate. Rather, those surface properties are adequate or inadequate in terms of specific vehicle maneuvers--stopping, turning, accelerating (i.e., vehicle demand for friction). This fact has been recognized directly or indirectly in a number of studies (5-10).

In the study by Ivey and Griffin (5), wet weather accidents were used as a surrogate for accidents that result from inadequate friction. Several variables were used as surrogates for vehicle demand for friction:

ADT = average daily traffic,
ACC = access (a standardized subjective scale of roadway congestion),
SN = skid number at 40 mph,
TW = proportion of time wet,
VM = mean traffic speed,
V = variation in traffic speed (one standard deviation from the mean), and
LN = lanes of traffic.

For 32 segments of highway on high-speed roads (55 mph), wet accident rates (WARs) ranged from 0 to 6.56. Approximately 58 percent of the variance in WAR could be accounted for by the following standard multiple linear-regression equation:

$$WAR = -21.7 + 0.0009\ ADT + 2.34\ ACC - 0.40\ SN + 286\ TW + 1.32\ LN \quad (3)$$

(Note that the units of WAR are wet pavement accidents per mile per year).

For 36 segments of highway on low-speed roads (<55 mph), the WARs ranged from 0 to 40.41. Approximately 46 percent of the variance in WAR could be accounted for by the following standard multiple linear-regression equation:

$$WAR = -0.75 + 0.0001\ ADT - 0.053\ VM + 0.54\ V + 0.69\ ACC - 0.025\ SN \quad (4)$$

Although Equations 3 and 4 still leave a large portion of the variation in the dependent variable unaccounted for, note that by tacitly taking demand for friction into account in these equations, much greater accuracy is achieved in predicting WAR than would have been possible on the basis of SN alone. This is emphasized by comparing the values of 58 and 46 percent (which roughly account for half the variation) to the values of 8.7 and 9.6 percent (which account for roughly one-tenth of the variation).

Surface Discontinuities and Traffic Accidents

The literature on the relationship between roadway discontinuities and traffic accidents is limited. Two studies, however, are applicable.

Ivey and Griffin (11) examined 15,968 single-vehicle accidents that occurred in North Carolina in 1974. Police officers' narratives for all 15,968 accidents were read by automated means. Any narrative that contained 1 of 19 key words (e.g., dip, rocks, rut, edge) was printed out and reviewed by the authors to determine if that accident resulted from, or was aggravated by, a roadway discontinuity. Approximately 566 (3.5 percent) of the 15,968 accidents were associated with roadway disturbances.

The data in Table 1 are adapted from the original report. Note that police accident reports are not always correct in indicating the elements that contribute to a specific accident because of a wide variation in experience and capability. Nevertheless, even with this known shortcoming, the keyword-narrative data-retrieval system developed by the North Carolina Highway Safety Research Center is a powerful tool.

TABLE 1 Number of Accidents from Discontinuity (Key Word)

Disturbance	Frequency	Disturbance	Frequency
Water	143	Patch	11
Dropped	73	Bump	9
Soft	71	Dip	9
Curb	62	Rocks	4
Edge	59	Ruts	4
Hole	34	Track	3
Rail	24	Rut	2
Drop	23	Manhole	2
Rock	19	Bumps	2
Surface	12	Total	566

The authors inferred that approximately half of the accidents reported in Table 1 resulted from a disturbance off of the traveled surface (e.g., "which dropped off the pavement," "vehicle hit curb and overturned") and half resulted from disturbances in the lane of travel (e.g., "vehicle hit bump in road," "ruts in road caused loss of control").

Klein et al. (12) reviewed accident data from three sources: California accident data (police level data), collision performance and injury report (CPIR) data provided by the Highway Safety Research Institute of the University of Michigan, and Indiana accident data (levels II and III) provided by Indiana University. Their findings are based on 23 hard copies from the California files, 26 from the Michigan files, and 22 from the Indiana files. The authors conclude that the most significant roadway disturbance is shoulder drop-off, closely followed by loose material on roadway. Lesser disturbances include potholes, rough roads, dips, and roadway design faults.

Although most authorities would agree that road surface discontinuities may precipitate or aggravate accidents, the magnitude of the problem is unknown. Indeed, the relative hazard of different disturbances and discontinuities is not well known.

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CHAPTER 3 Roughness, Holes, and Bumps

James C. Wambold, Richard A. Zimmer,
Hayes E. Ross, Jr., and Don L. Ivey

Roughness

Most people are aware of extreme cases of roughness, such as the potholes and bumps shown in Figure 1. The effect of these surface irregularities on safety is widely recognized. The hazard of a washboard road (Figure 2), where a driver can lose control of a vehicle at high speeds, is readily understood. However, the transition of a roadway from a smooth surface to a rough one (Figure 3), which may give a driver difficulty in controlling his vehicle, can be more subtle in its influence on safety. By violating driver expectancy, a road that is differentially rough may be less safe than a uniformly rough road.

Studies of the effects of roughness on vehicle handling characteristics were conducted in 1972 by Quinn and Hildebrand (1,2), by Brickman et al. (3), and by Wambold et al. (4). These studies demonstrate that pavement roughness had an effect on the tire-pavement friction available to the vehicle. The Quinn and Hildebrand study demonstrated the effect of pavement roughness on steering, and the study by Wambold et al. demonstrated the effect of pavement

FIGURE 2 Road with washboard sections (control may be lost at speeds greater than 35 mph).

FIGURE 1 Potholes and bumps in combination.

FIGURE 3 Relatively smooth road suddenly changing to a rough downhill section.

roughness on traction. The relation between road roughness and accident risk was reported by Parr in 1973 (5). In 1975 Hutchinson et al. (6) reported that traction is highly dependent on the speed at which a driver traverses a rough road; thus when frictional measurements are made at speeds other than the test speed, road profile data should be considered. Therefore, frictional predictions without profile considerations can result in gross errors. In 1976 Ivey and Griffin (7) reported on the relationship between road surface failures and accident causation. In that paper a group of engineers ranked a number of surface conditions in relation to safety, based on their understanding of vehicle dynamics, potential surface conditions, and experience. According to that ranking, washboarding, or corrugated surfaces, was a leading condition pertaining to the pavement surface that affected safety.

In 1977 Magnusson and Arnberg (8) reported that road roughness affects a driver's ability to collect information and carry out intended maneuvers; and roughness also forces the effects of external disturbances. They also reported that a person's ability to perform motor tasks has been shown to be reduced by vibrations, but it is not known to what degree the findings are applicable to vibrations encountered on a rough roadway. In 1977 Bohn and Dunkle (9) and in 1980 Kuehne and Bohn (10) simulated the effects of road roughness on pavement loading and traction. Although the way roughness reduces available pavement friction was illustrated, it was determined that a better tire-road model would be required to achieve accurate quantitative results. In a recent paper Burns (11) concluded that roughness affects safety in many ways, and it needs to be considered in any evaluation of pavement safety. He noted that roughness can reduce the steering and braking force and can significantly affect the controllability of a vehicle. Washboarding surfaces and repeated cycling undulations of the surface can cause significant control problems and can shake a vehicle, thus causing it to lose part of its load. In another paper Molenaar and Sweere (12) concluded that rough roughness appears to have a marked effect on road user safety.

A study currently under way at the Pennsylvania Transportation Institute makes use of a circular track developed by R.R. Hegmon. This track has been modified so that roughness of a known amplitude and wavelength can be inserted in a wheel track. Testing is currently being conducted to evaluate the full suspension of a vehicle. The first series of tests involved the use of a vehicle front end to evaluate the changes in traction as a function of the amplitude and wavelength of the roughness. Future studies will involve not just circumferential traction, but also cornering forces. A separate study has resulted in the installation of a roughness calibration facility that will allow further investigation of the effects of roughness on traction.

One factor that is probably the least understood is the effect of vehicle vibration induced by road roughness on driver performance. It has been reported by human factors researchers that continuous exposure to vibration may induce fatigue, which may in turn be a factor that contributes to accidents. To date, no direct relationship between road roughness and fatigue-related accidents has been established. The International Standards Organization (ISO) standards provide a link between vibrations and fatigue, but the link between fatigue and highway safety is still missing and is perhaps a subject that might be pursued in further research.

Potholes

> Holes in the pavement have to be a foot or more long and wider than a tire to be hazardous. If a driver claims his vehicle was thrown out of control by a small hole, treat this statement with suspicion and look for driver actions which may be contributing factors, such as cutting back into lane after overtaking.... A vehicle can be turned over by hitting a chuck hole without signs on either the tire or the hole, especially when the edges of the hole are rounded.

With this statement Baker (13) gave credence to the danger of holes--a major example of discontinuities. Whether called pothole, chuck hole, or any other colloquialism, the nature of such a hole is to be hard on tires, vehicles, and drivers' tempers. But are they a significant direct threat to safety? This alleged influence on safety may be highly inflated by many accident reports that reflect driver frustrations and excuses.

Accident reports state that holes are a causative factor in many accidents. In 1976 Ivey and Griffin (7) reported a rank ordering of roadway disturbances based on 15,968 accidents in North Carolina. Hole was mentioned in 34 reports that ranked hole sixth out of 19 disturbances behind the key words water, dropped, soft, curb, and edge. In a Delphi ordering developed by the same authors, holes ranked eighteenth out of 20 disturbances.

In 1977 Klein et al. (14) completed a study of the influence of roadway disturbances on vehicle handling. The accident data cited were difficult to interpret because of the extremely small sample size from each source. As part of this study a questionnaire was sent to the membership of the Automobile Club of Southern California. Twenty-eight percent (1,412 individuals) responded. Holes ranked third out of 13 identified disturbances in terms of a driver's perception of hazard. It appears that, whether justified or not, holes are clearly perceived to be a significant threat to safety. It is also clear that this public perception is not shared by many engineers who have significant knowledge of vehicle handling and stability characteristics.

To clarify this apparent difference in opinions, Zimmer and Ivey (15) conducted a series of controlled vehicle-hole interaction experiments. With holes as large as 3 ft long (diameter) and 7 in. deep, the stability of vehicles was not affected. That is, the trajectory, or vehicle path, was not changed. The only safety-related influence of holes identified was damage to tires and rims, with the associated potential for an air-out. Figure 4 shows one of the tests conducted on naturally occurring holes. By controlled experiments and computer modeling, the drop rates of various automobile suspension systems were determined. The information was then combined with observed tire deformation effects to determine the limits of safety (see Figure 5).

As illustrated in Figure 5, the critical point for a particular vehicle and speed combination is first located by a combination of full-scale tests and computer modeling. A line is extended up and to the right from that point. The area cut off by the two arrows (i.e., the area of the chart above and to the right of the intersection of arrows) represents those combinations of hole length and depth that could produce a potentially hazardous condition. Conversely, the area to the left and below the in-

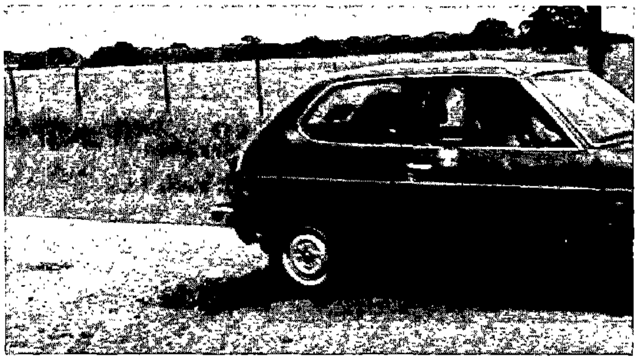

FIGURE 4 1978 Honda CVCC traversing hole 40 in. deep and 8 in. long.

tersection of arrows indicates relatively safe hole sizes for the indicated speed.

Figure 6 is a generalization of Figure 5, where three bands of safety are shown based on the four test vehicles evaluated. The first band (left and lower) defines hole length and depths referred to being reasonably safe (where a prudent driver of a reasonably maintained vehicle would experience no significant problem in traversing a hole). The middle band, which is bounded by the upper and lower extremes of tested vehicles, represents an area of questionable safety, where a vehicle could sustain tire, rim, or suspension damage when traversing a hole with the defined dimensions. Finally, the unsafe band defines length and depth combinations that might produce a hazardous condition for any of the four vehicles tested.

Although the choice of vehicles tested by Zimmer and Ivey (15) would appear to be adequate to define a fairly wide spectrum of vehicle characteristics, this has not been experimentally verified. Parameters such as inertial properties, spring stiffness, and tire stiffness should be considered to objectively evaluate the sprectrum of vehicles encompassed. Other factors such as vehicle loading and the influence on vehicles other than four-wheeled passenger vehicles were not considered. There are probably no two potholes alike in terms of shape, edge slope, and bottom contour. This study used a definable edge, which was square, with vertical sides and a level bottom. This approach provided insight into a worse-case situation, which may encompass only a small number of highway potholes. It does, however, permit conservative safety predictions, because any sloping of the sides will only produce a safer condition for a given size hole.

It is apparent from the study by Zimmer and Ivey that a hole must be relatively large to constitute a significant influence on safety when rim or tire damage are the guiding criteria. At common highway speeds in excess of 40 mph, a hole must be in excess of 60 in. long and 3 in. deep to constitute a threat to the smallest automobiles. On urban streets with traffic speeds as low as 20 mph, holes must still be more than 30 in. long and more than 3 in. deep to have the potential of damaging tires and rims.

Damage to tires and rims, with the associated potential for an air-out, is the only significant influence of holes on safety identified in the study by Zimmer and Ivey. Holes are atypical of most highway surface discontinuities in that they have a greater potential to cause damage at lower vehicle speeds. A vehicle with an air-out is obviously much easier to cope with at 30 mph than at 60 mph. The result of these two effects is that the usual size hole a driver encounters is not likely to be a major problem when struck directly.

Problems can arise if a driver reacts to a hole inappropriately. For example, it is counterproduc-

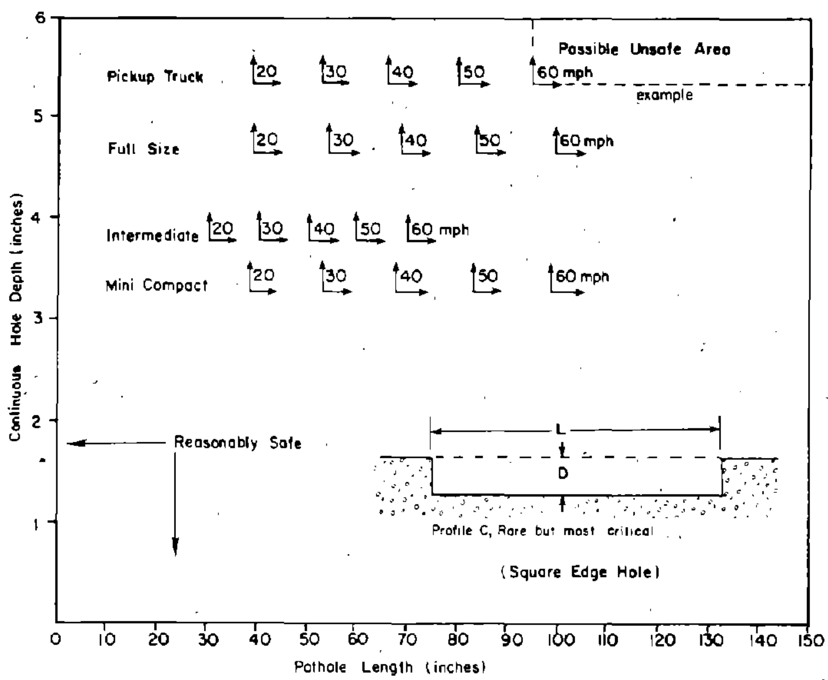

FIGURE 5 Critical combinations of hole length and depth for various speed and vehicle situations.

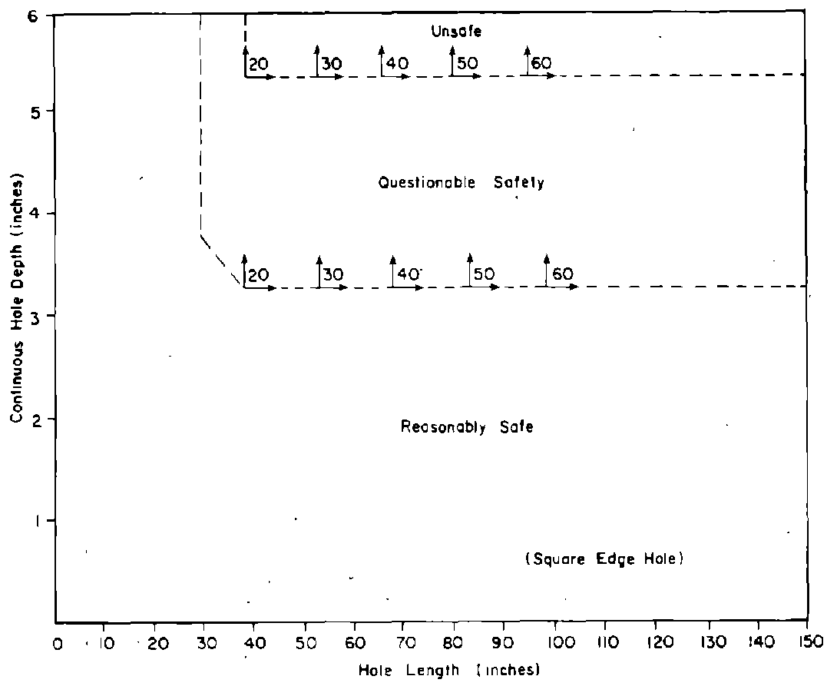

FIGURE 6 Generalized zones of safety for hole length and depth combinations.

tive to react with braking or extreme cornering to a hole in the vehicle's path. In general, a given size hole is more likely to cause damage if speed is reduced. Losses of control can occur if extreme braking is produced at highway speed. Extreme cornering can have two results. First, if a driver reacts with a large steering input to avoid a hole, he may produce a loss of control on a low friction surface. Second, he may put his vehicle in a hazardous position with respect to other traffic. In the authors' opinion, it is probably the latter maneuver that accounts for most of the accidents where holes are identified as having an influence on driver safety.

The influence of holes encountered when cornering deserves further attention. A cornering (turning) vehicle transfers weight from the wheels on the inside of the turn to the outside wheels. The springs on the heavily loaded side are compressed. When one of these tires encounters a hole it goes down faster because of the acceleration of the higher spring force. Thus it is in position to be damaged more quickly (down farther in a given length of hole for a specific speed) than is represented in Figure 5. A second and potentially more hazardous situation is if a tire is moving laterally and encounters the side of a hole. A trip and roll could possibly occur in this situation, but it would require the car to be in an extreme lateral drift (skid). This lateral drift would need to be so extreme that it would be associated with intemperate vehicle control or a loss of control that preceded contact with the hole. It could be that first-hand knowledge of an event such as this, even though it is likely to be rare, led Baker (13) to say that "a vehicle can be turned over by hitting a chuck hole...."

The purpose of this work is not to conclude that holes in highway surfaces should be tolerated. The many disadvantages of these flaws dictate their elimination within the bounds of financial constraints. In this day of highways that are "past maturity and in future shock" (16), it is unlikely that the public will choose to fund the maintenance required to make holes an endangered species. Instead, the purpose of this work is to put the influence of holes on safety into perspective so that maintenance activities can be appropriately made priority items.

In summary, it appears improbable that any but the largest holes cause significant control problems. Exceptions may be a large number of holes in a small area that cause extreme roughness, especially where maneuvers such as braking or cornering are required. Under some highway conditions, the slower the speed is of a vehicle, the larger is the impact force for a given size hole. Although tire or rim damage may be more probable at lower speeds for deep holes, the result of such damage will be easier for the driver to accommodate. The greatest influence of holes on safety may be the hazard caused by drivers trying to avoid them.

Curbs

Curbs and gutters were used to facilitate the ingress and egress of carriage riders and later automobile passengers, to control roadway drainage, to help delineate the edge of the travelway, and to afford protection for pedestrians. As paved roadways branched out into the rural areas, so did the use of curbs. Early standards and guidelines published by federal and state agencies promoted their use on rural highways and urban streets.

Two basic types of curbs have been used for many years. Barrier curbs, which were designed to prohibit or discourage encroachments are relatively high and steep faced. Mountable curbs, which were designed to enable vehicles to cross them readily, are relatively low, with flat sloping faces. Details of widely used curbs of each type can be found in the AASHO Blue Book (17).

Studies in the 1950s by Benton and Peterson (18) and Benton and Field (19) were some of the first to note the potential safety problems with curbs.

Vehicle jump subsequent to impact with the curb was observed, and recommendations were made regarding barrier height as a function of barrier setback from the curb. In 1964 the Highway Research Board Special Report 81 (20) alluded to possible problems if high curbs are used in front of guardrails.

The first Yellow Book published by AASHO in 1967 (21) stated that "a dike or curb should not be used in front of guardrail where it may result in a dynamic jump by the vehicle before it strikes the barrier." NCHRP reports by Michie and Calcote (22) and Michie and Bronstad (23) recommended that curbs be placed behind guardrail. The Red Book published by AASHO in 1973 (24) pointed out the need for relatively flat surfaces in front of barriers. It stated that barrier curbs should not be used on freeways and high-speed arterials. The second Yellow Book published in 1974 (25) reflected these recommendations.

In 1974 Olson et al. (26) reported on a number of actual vehicle tests and computer simulations of vehicle behavior subsequent to impact with various curb types. The report concluded that "it has been found that curbs offer no safety benefit on high-speed highways from the standpoint of vehicle behavior following impact." The AASHTO barrier guide of 1977 (27) concluded that a curb should not be used as a redirective device, and if it is used with a barrier, the face of the curb should be no closer to the traveled way than the face of the barrier.

A recent study by Griffin (28) indicated that small cars are more likely to be involved in curb accidents than are large cars. This appears to be a logical consequence, because handling and stability problems associated with car-curb involvements should be inversely related to wheel size.

The literature and data in the report by Griffin strongly suggest that the hazards curbs present to errant motorists on high-speed facilities in terms of potential loss of vehicle control, potential overturning, and incompatibility with barrier performance outweigh those benefits that may accrue as a result of improved delineation, drainage, and traffic control. On most high-speed facilities, delineation, drainage, and traffic control can be treated better by other means.

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CHAPTER 4 Pavement Edges

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Eric F. Nordlin, and Richard A. Zimmer

The Phenomenon

An abrupt difference in elevation between two adjacent riding surfaces can occur at the joining of (a) a paved traveled way and an unpaved shoulder, (b) a paved traveled way and a paved shoulder, (c) a paved shoulder and an unpaved adjacent area, or (d) two traveled lanes. If this difference in elevation reaches certain levels for certain edge shapes, safety can be affected.

Pavement edge drops can be produced when the longitudinal edges of an asphalt concrete pavement lift are not tapered to become flush with the surface of the existing paved shoulders. Edge elevation differentials are a necessary temporary situation at the edge of a pavement overlay until the adjacent overlay can be placed. Another common pavement edge drop can result from the displacement of untreated shoulder material from the edge of the traveled way caused by vehicle tire contacts or erosion from wind, rain, or other environmental conditions.

The pavement edge elevation differentials considered here range in height from less than 1 in. to 6 in. The edge drop-offs created by trenching for the construction of pavement widening, edge subdrainage systems, and so forth are deeper and constitute more obvious traffic safety problems.

Pavement edges can affect vehicle control because of inappropriate action or inaction by a driver. The following scenario describes some of the elements of an edge drop.

1. A vehicle is under control in a traffic lane adjacent to a pavement edge where an unpaved shoulder is lower than the pavement.
2. Through inattention, distraction, or some other reason the vehicle is allowed to move into a position with the right wheels on the unpaved shoulder and just off the paved surface.
3. The driver then carefully tries to gently steer the vehicle to gradually bring the right wheels back up onto the paved surface without reducing speed significantly.
4. The right front wheel encounters the pavement edge at an extremely flat angle and is prevented from moving back onto the pavement. The driver further increases the steer angle to make the vehicle regain the pavement. However, the vehicle continues to scrub the pavement edge and does not respond. At this time there is equilibrium between the cornering force to the left and the edge force acting to the right, as shown in Figure 1a.
5. The driver continues to increase the steer input until the critical steer angle is reached and the right front wheel finally mounts the paved surface. Suddenly, in less than one wheel revolution, the pavement edge force has disappeared and the cornering force of the right front wheel may have doubled because of increases in the available friction on the pavement and the increases in the right front wheel load caused by cornering (see Figure 1b).
6. The vehicle yaws radically to the left, pivoting about the right rear tire, until that wheel can be dragged up onto the pavement surface. The excessive left turn and yaw continues, and it is too rapid in its development for the driver to prevent penetrating the oncoming traffic lane (Figure 1c).
7. A collision with oncoming vehicles or spin out and possible vehicle roll may then occur.

In many situations vehicle loss of control may not develop because the driver steers more aggressively. By moving back onto the pavement at a slightly sharper angle and increased lateral velocity, the scrubbing action on the face of the pavement drop-off can be avoided. In many cases, however, the same result--vehicle loss of control--may occur without the influence of a pavement edge drop. A loose, muddy, or low-friction shoulder can have the same effect if the driver oversteers when trying to return to the paved surface. Often it is this oversteering that is the cause of an accident when a pavement edge drop of modest height is blamed.

The qualitative effect of pavement edges, or the so-called lip drop-off, has been to some degree understood for many years. In Baker's Traffic Accident Investigator's Manual (1) published by Northwestern University, the following statement is found: "Lip drop-off is simply a low shoulder at the edge of a hard pavement. It is important when the shoulder is more than three inches below the pavement...." Based on a telephone conversation with Baker on September 22, 1982, it was determined that this conclusion was

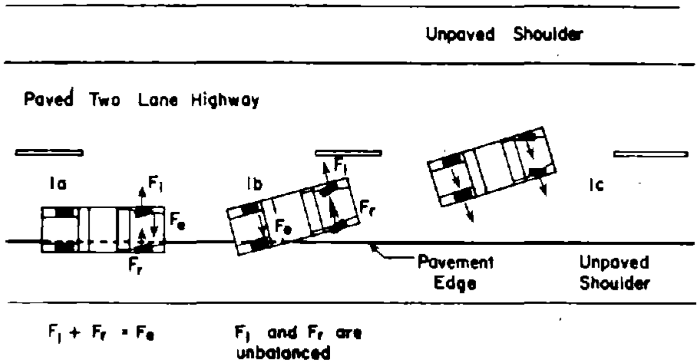

FIGURE 1 Illustration of the pavement edge influence on vehicle stability.

reached by informal testing at Northwestern as early as 1959.

Testing and Analysis

In 1974 the California Department of Transportation (Caltrans) studied several highway accident cases where pavement edge drops were cited as a contributing factor. There were contentions that a drop-off height as small as 1 to 2 in. would throw a vehicle out of control as it tried to climb back up the pavement edge, that the steering wheel would be wrenched out of the driver's hands, and that the vehicle would be forced into a path into the opposing lanes before it could be straightened out. As a result, Nordlin et al. (2,3) conducted a number of vehicle tests under various conditions to confirm or refute some of the claims that were being made and, in general, to observe the effects of pavement edge drops on vehicle stability and controllability.

Fifty tests were conducted by using a professional driver to compare the following test conditions:

1. Three drop-off heights--1.5, 3.5, and 4.5 in.;
2. Four test vehicles--small, medium, and large passenger automobiles and a pickup truck;
3. Two surface conditions--an asphalt concrete (AC) shoulder that dropped off to a compacted soil surface, and an AC shoulder that dropped off to another AC paved surface; the AC shoulder drop-off edges were nearly vertical and slightly irregular with minor cornering raveling; and
4. Two vehicle trajectories--with only the two right wheels dropping off and then coming back up onto the AC pavement, and next with all four wheels dropping off onto the shoulder and then returning back up onto the AC pavement.

The driver, a former race car driver, was a private consultant who conducted vehicular impact tests and other automotive research. In all of these tests the driver eased the test vehicle at about 60 mph out of the far right traveled-way pavement lane, across the 5-ft-wide AC shoulder, over the edge drop-off at angles of 1 to 7 degrees (generally 3 to 5 degrees), straightened the vehicle, climbed up the drop-off at angles of 1 to 8 degrees (generally 3 to 5 degrees), and eased across the AC shoulder back into the adjacent far right traveled-way lane. The path of the right tires during the two-wheel drop-off tests and the left tires during the four-wheel tests reached a distance of at least 1 ft and usually about 3 ft to the right of the drop-off edge.

The following observations were reported in regard to the formal tests in the Nordlin study.

1. The pavement edge drops did not throw the vehicles into an unstable condition or cause the driver to even come close to losing control during any of the tests.
2. For almost all of the steering maneuvers, the steering wheel was turned through an angle of 60 degrees or less. The driver handled the steering wheel with minimal effort at all times. In several of the tests he even held the wheel lightly with the thumb and forefinger of each hand. There was no difference in performance between vehicles with and without power steering.
3. It took less than one wheel revolution for the leading wheel to climb the drop-off once the pavement edge was contacted; thus tire scrubbing was negligible. Varying amounts of front wheel wobble occurred when the leading wheel mounted the 3.5- and 4.5-in. drop-offs. This was caused by the interaction of the tire sidewall and the irregular pavement edge. The driver felt a significant jolt and heard an accompanying loud front-end noise when the vehicles dropped off or remounted the 3.5- and 4.5-in. pavement drop-offs. A minimum roll angle of 10 degrees (generally 3 to 7 degrees) occurred when the vehicles went off and back up the drop-offs. However, none of these occurrences affected the trajectory of the vehicle in any of the tests. In all of the tests the vehicle traveled on a smooth path after climbing the drop-off without overshooting beyond the nearest traveled-way pavement lane.
4. During the formal test series two nonprofessional drivers (a male and a female) did not encounter any stability problems or have any steering difficulties while informally driving the medium and large passenger automobiles over and back up the three drop- off heights at speeds of 40 to 45 mph.

In 1978 Stoughton et al. (4) conducted several tests involving a broken, crumbling AC pavement edge and a 2-in. drop to the surface of an adjacent muddy soil shoulder. The same professional driver from the Nordlin study drove a pickup truck at 60 mph on a trajectory with only the two right wheels dropping off and coming back up onto the AC shoulder. Because the tires sank in the mud, the overall drop-off height was 2.75 in. where the truck returned to the pavement. No problems with vehicle stability or controllability occurred in driving the test course.

In 1976 Klein et al. (5) conducted a roadway surface study that included pavement edge drops. In the study accident data and public inquiries through questionnaires were analyzed, and a variety of both open- and closed-loop tests were conducted. Naive drivers were used in the closed-loop tests. In all of the pavement edge drop-off tests, a special effort was made to achieve the tire scrubbing condition before attempting to climb up the drop-off. In edge drop tests with drop-off up to 5 in. and the scrubbing condition, losses of vehicle control were encountered at higher speed levels, generally more than 30 mph. Klein et al. made a major contribution in defining a control difficulty parameter, T_{r_c}, and relating it to a critical speed for each test vehicle. They found that a value of about 0.6 sec for T_{r_c} accurately represented the limiting situation for not exceeding the lane boundary after a 4.5-in. climb. Referring to Klein's curve [Figure 2 (5)], speeds greater than 32 mph for the Pinto and the Caprice Wagon and greater than 44 mph for the Nova result in values of control difficulty that exceed 0.6 sec. These same speeds were found to be the

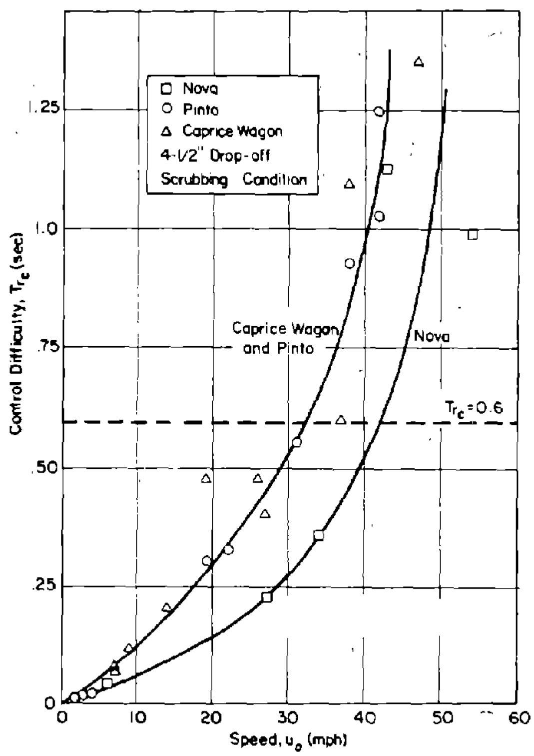

FIGURE 2 Control difficulty parameter versus vehicle speed *(5)*.

critical speed for the lane boundary not being exceeded during the closed-loop test with a 4.5-in. drop-off. The equation for T_{r_c} (control difficulty parameter) is

$$T_{r_c} = (M \cdot U_o)/(2 \cdot Y_{local}) \quad (1)$$

where

M = vehicle mass,
U_o = forward speed, and
Y_{local} = local slope of cornering stiffness curve (i.e., the slope of the cornering force versus slip angle curve at the point the tire mounts the pavement edge).

Klein et al. found the time between edge mounting of the front and rear tires to also be less than 0.6 sec. As shown in Figures 3 (5) and 4 (5), they also developed curves for the relationships between steering wheel angle and the vehicle steer angle required to climb various vertical pavement edge

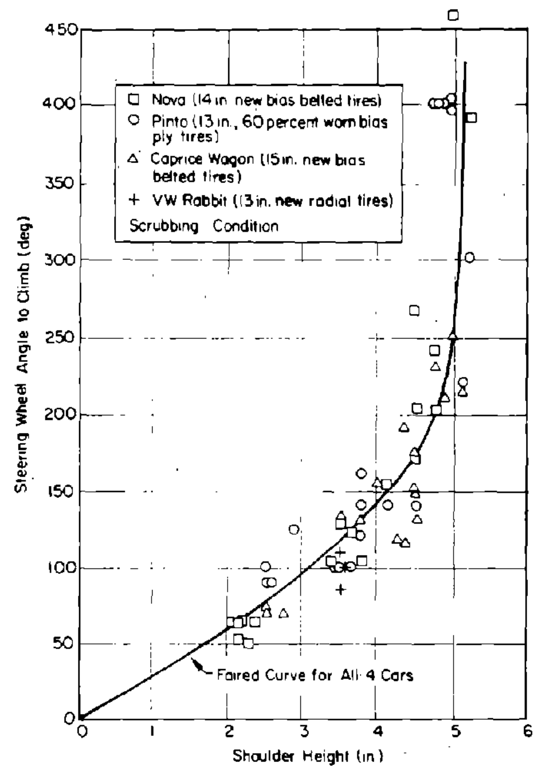

FIGURE 3 Steering wheel angle versus pavement edge height *(5)*.

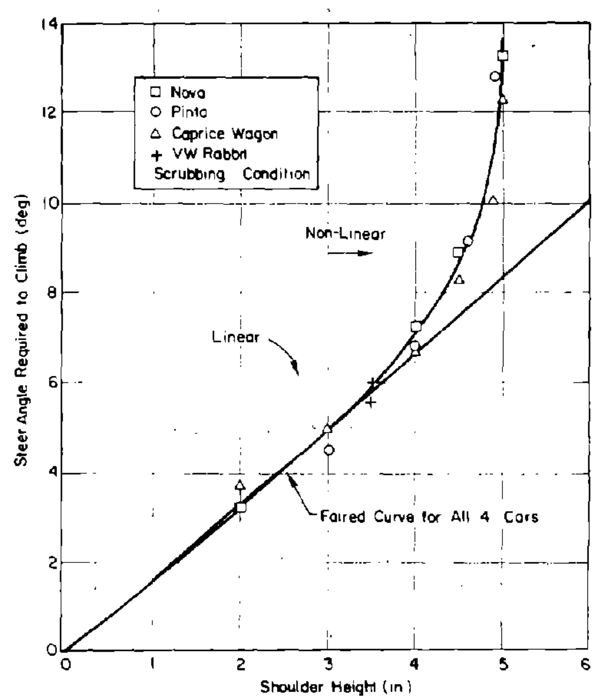

FIGURE 4 Steer angle required for different edge heights *(5)*.

heights from the scrubbing condition. For edge heights up to 3 in., both curves are relatively linear. In this range the edge-climbing maneuver appears relatively safe. As the curves become more curvilinear, the maneuver becomes significantly more difficult. As the curves start a precipitious rise, again approaching a straight line, the difficulty becomes extreme.

The Nordlin and Stoughton studies had not included the pavement edge-scrubbing condition, and the Klein study had concentrated almost entirely on the edge-scrubbing condition and one pavement edge geometry, that is, vertical with little edge rounding. Therefore, Zimmer and Ivey (6) in 1981 undertook a new study to extend the information already developed by Nordlin, Stoughton, and Klein.

The comprehensive test program developed by Zimmer and Ivey to evaluate the effects of pavement edge height situations included the following test conditions:

1. Three edge heights--1.5, 3, and 4.5 in.;
2. Four test vehicles--mini-compact, intermediate and full-sized passenger automobiles, and a pickup; weights varied from 1,668 to 4,713 lb, and wheel sizes varied from 12 to 15 in.;
3. Two tire constructions--the intermediate and full-sized automobiles were tested with both bias ply and radial tires; the other two vehicles were tested with only radial tires;
4. Three pavement edge drop geometry profiles--shape A = vertical with minimal corner rounding, shape B = fully rounded, and shape C = 45-degree slope;
5. Three test speeds--35, 45, and 55 mph;
6. Four drivers--a professional driver who teaches high-performance driving techniques, a semiprofessional driver who occasionally perform as a test driver, a typical male driver (a construction supervisor with no special driving skills), and a typical female driver (a technician with no special driving skills); and
7. Three vehicle trajectories--with only the two right wheels dropping off the pavement onto the earth shoulder and then moving back at an extremely flat angle to produce the edge-scrubbing condition before attempting to maneuver back up onto the pavement; with only the two right wheels dropping off but returning at a comfortable but sharp enough angle to preclude any continuous edge-scrubbing action; and with all four wheels dropping off onto the shoulder and returning at a sharp enough angle to minimize the edge-scrubbing action.

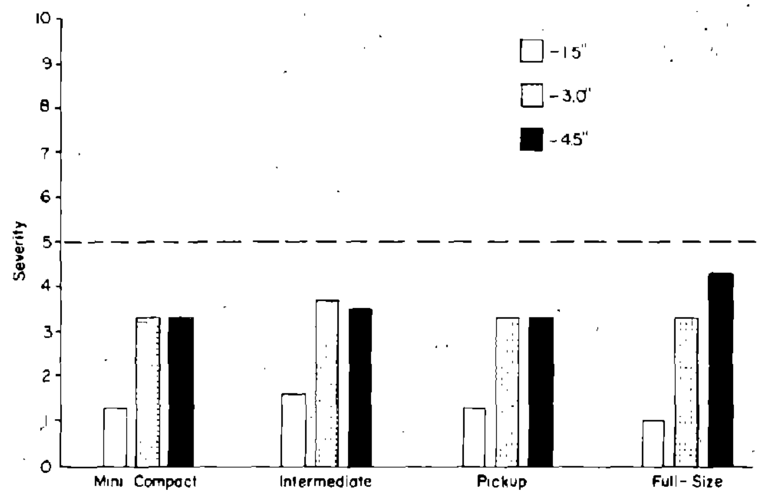

FIGURE 5 Severity rating situation for different edge heights (nonscrubbing condition, edge shape A) *(6)*.

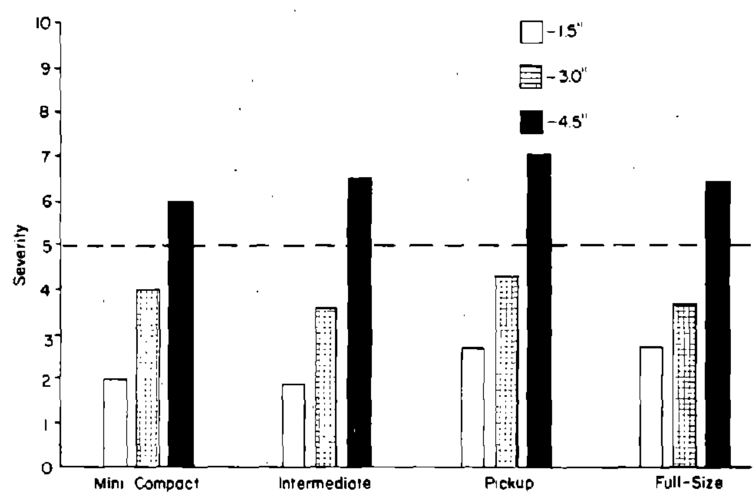

FIGURE 6 Severity rating situations for different edge heights (scrubbing condition, edge shape A) *(6)*.

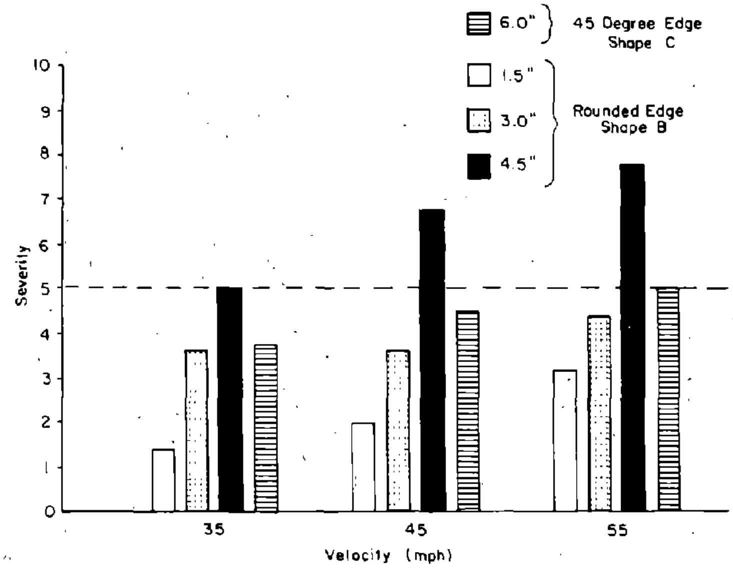

FIGURE 7 Effect of vehicle speed on maneuver severity *(6)*.

In addition to photographic and electronic data, the drivers expressed the severity of each test run immediately after completion by the following numerical ranking: 1 = undetectable, 2 = very mild, 3 = mild, 4 = definite jerk, 5 = effort required, 6 = extra effort, 7 = tire slip (slight lateral skidding), 8 = crossed centerline and returned, 9 = crossed centerline and no return, and 10 = loss of control (spin out).

Even though this system is subjective and prone to variability from driver to driver, it proved to be a satisfactory indicator when confined to any one driver's reaction to the entire matrix of tests. This rating value was later used as the independent variable when sorting the various combinations of conditions by computer.

Figures 5 (6) and 6 (6) show the average rating values for the tests involving the professional driver, the two-wheels-off trajectory, and the shape A pavement edge profile. However, Figure 5 presents the values for only the nonscrubbing tests. As can be seen, there is little difference either between vehicles or between the 3- and 4.5-in. heights. In comparison, Figure 6 shows the ratings for only the tests where the vehicle wheels were purposely put into intimate scrubbing contact with the edge before a return to the pavement was attempted. The difference between vehicles was small, but the effect of edge height was pronounced. For all vehicles, the maneuver-severity bars for the 4.5-in. heights extend into the upper half (critical range) of the chart.

Figure 7 (6) shows the effect of vehicle speed on the severity of the maneuver by the professional driver over shape A in the two-wheels-off trajectory with scrubbing action. All vehicles were averaged because vehicle differences were shown to be small. The maneuver-severity increase is almost linear as the speed increases for each drop-off height. As before, the 4.5-in. height is a potentially unsafe condition even at a speed as low as 35 mph.

Summary of Findings

The results of the work by Zimmer and Ivey under the edge-scrubbing condition are summarized in Figure 8

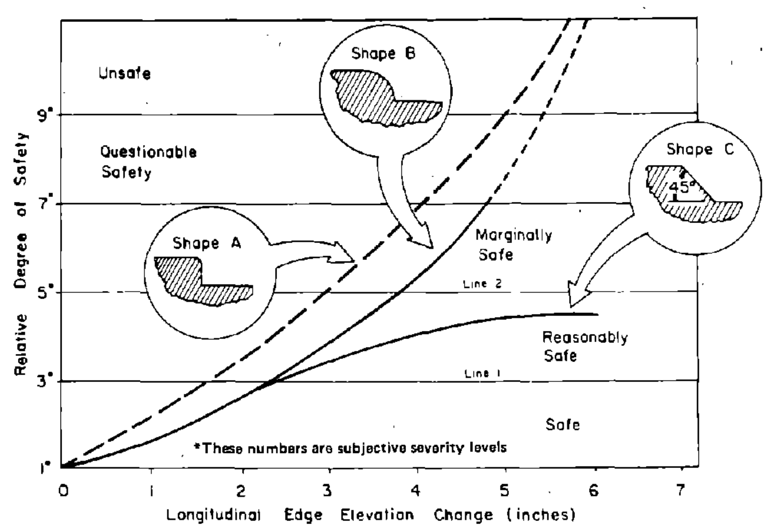

FIGURE 8 Relative degrees of safety for various edge conditions *(6)*.

(6), where the relative degree of safety, in terms of the subjective severity levels defined previously, is plotted against the longitudinal edge elevation change (drop-off). The terms describing the relative degrees of safety are defined as follows.

- Safe: No matter how impaired the driver or defective the vehicle, the pavement edge will have nothing to do with a loss of control. This includes the influence of alcohol or other drugs and any other infirmity or lack of physical capability. (Includes subjective severity rating values 1 through 3.)
- Reasonably safe: A prudent driver of a reasonably maintained vehicle would experience no significant problem in traversing the pavement edge. (Includes severity values 3 through 5.)
- Marginally safe: A high percentage of drivers could traverse the pavement edge without significant difficulty. A small group of drivers may experience some difficulty in performing the scrubbing maneuver and remaining within the adjacent traffic lane. (Includes severity values 5 through 7.)
- Questionable safety: A high percentage of drivers would experience significant difficulty in performing the scrubbing maneuver and remaining in the adjacent traffic lane. Full loss of control could occur under some circumstances. (Includes severity rating values 7 through 9.)
- Unsafe: Almost all drivers would experience great difficulty in returning from a pavement edge scrubbing condition. Loss of control would be likely. (Includes subjective severity values 9 and 10.)

Figure 8 includes curves for the three pavement edge profiles. The data in the figure indicate that the shape A profile is safe or reasonably safe under the scrubbing action for drop-off heights up to and including 3 in. Under the same conditions, shape B is safe or reasonably safe for drop-off heights up to 3.75 in. Zimmer and Ivey (6) conclude that shape C would only be a problem when the vehicle suspension or other underbody elements contacted the pavement edge. For this shape, an edge drop height of 5 in. might be reasonably safe for even the smallest current automobile.

Figure 8 could also be used to develop recommendations for maintenance. For example, the shape B curve crosses line 1 at about the 2.5-in. drop-off height. This might be the signal that it is time to schedule maintenance activities to prevent the height from increasing beyond 3.75 in. (the crossing of line 2), where the drop-off becomes marginally safe for the edge-scrubbing condition. The advantage of avoiding shape A is also apparent from Figure 8. If shape C can be constructed, either during original construction or as a maintenance activity, the need for edge maintenance could be significantly reduced. Shape C may also have significant advantage in resisting pavement edge deterioration.

In summary, the results of published studies on the influence of longitudinal pavement edges on vehicle safety are consistent and supplement each other. It is agreed that loss of vehicle control can develop at speeds greater than 30 mph under certain circumstances, where inattentive or inexperienced drivers return to the traffic lane by oversteering to overcome the resistance from a continuous pavement edge and tire-scrubbing condition. This safety problem is minimized where the pavement edge drop does not exceed 3 in. in height or the face has a 45-degree slope. A loose or muddy soil shoulder should not increase the edge-climbing difficulty, provided that the overall height is the same. However, similar-looking losses of control can occur even without any edge drop when an errant vehicle is returned to the higher surface friction of the pavement by oversteering. Pavement edge heights more than 5 in. in height can interfere with the underneath clearance and thus create safety problems for small automobiles.

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CHAPTER 5 Friction Variations

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Transverse Friction

Transverse variations of friction across a lane, sometimes called differential friction, can cause significant problems for a braking vehicle. This condition arises when the individual wheel paths on which a vehicle's tires ride have significantly different coefficients of friction. This problem may be minor or extremely serious, depending on the magnitude of the frictional difference, its relationship to the average coefficient of friction, and the speed at which a vehicle travels across the surface.

This phenomenon was first described theoretically by Zuk (1) in 1959. Zuk developed equations to predict the total yaw angle of a vehicle based on its mass, speed, and the coefficient of friction for each of the wheel paths. Zuk concluded that a difference in the friction coefficients of the wheel paths could be potentially hazardous even though the average surface friction was relatively high.

Fifteen years later Burns (2) provided further information on this subject by performing braking tests using various vehicles under highway conditions. These tests provided detailed observations of the movement of vehicles braking on split-friction surfaces, as well as indications of the relative controllability of vehicles under those conditions. An example found on the highway during Burns' study was where the left wheel path was bleeding and the right wheel path was chip-sealed. The right wheel path had a wet stopping distance number (SDN_{40}) of 67 and the left had a wet SDN_{40} of 41. This difference of 26 represents a 63 percent braking force differential. A car braking at 40 mph on this surface rotated 90 degrees clockwise. The same car braking at 50 mph rotated 270 degrees clockwise. The results of these tests are shown in Figure 1 (2).

Burns developed equations to predict the amount of rotation that would occur for a vehicle braking on a surface, given specific levels of differential friction, average coefficient of friction, and speed. He suggested that a surface that produced total rotations greater than those listed in the following table could create a major loss of vehicle control while braking:

Speeds at Which Wheels Are Locked (mph)	Total Rotation After Car Has Stopped (°)
30	30
40	50
50	70

This research also identified the most commonly found differential wheel path conditions. They are (a) differential flushing or bleeding, (b) unequal wear, (c) partial seal coating of a lane, (d) dissimilar shoulder surfaces, (e) maintenance crack

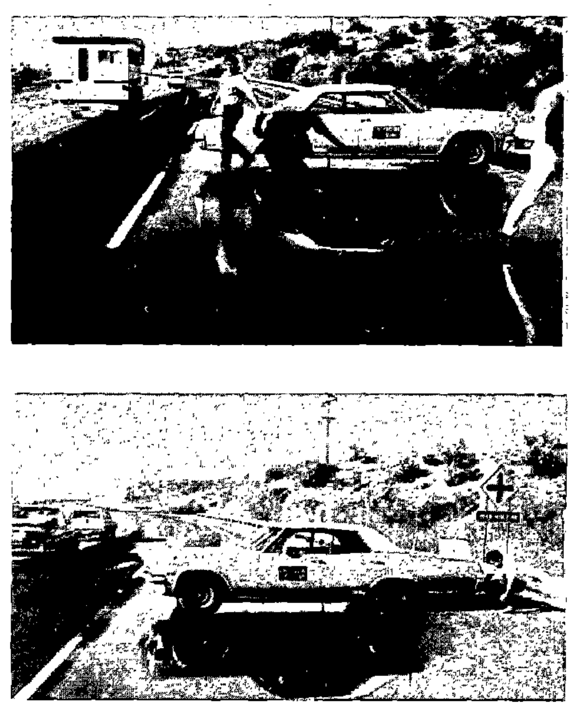


FIGURE 1 Vehicle rotation during stopping maneuver *(2)*—top: 90-degree clockwise rotation at 40 mph; bottom: 270-degree rotation at 50 mph.

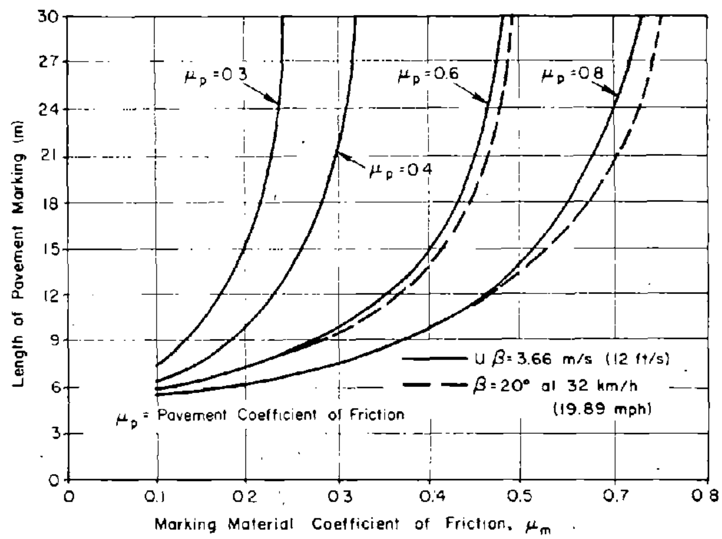


FIGURE 2 Recommended maximum lengths of differential friction for safe operation of cars during hard braking conditions (vehicle initial speed is 55 mph) *(3)*.

patching of only one wheel path, and (f) unequal drainage properties.

In 1981 Hayhoe and Henry (3) conducted research to better determine the levels of acceptable differential friction. A simulation of the skidding behavior of cars in plane rotation on differential friction surfaces was used to develop the curves shown in Figure 2 (3). These curves are used as follows. μ_1 is the higher of the two coefficients. Plot the position of the lower coefficient (μ_2) and the length of the split-coefficient surface. If the resulting point is to the left of the μ_1 curve, the situation is potentially unsafe; if it is to the right, a relatively safe situation is indicated.

These and other studies have confirmed that differential friction can have a significant effect on a braking vehicle. The vehicle-rotation phenomenon can occur at high as well as low friction levels and should be considered in any pavement friction evaluation. The greatest problem arises when the driver releases his brakes after the car has begun to spin. When this is done the vehicle is propelled in the direction it is facing. This could be off the road or into oncoming traffic. Thus the greater the degree of rotation, the more uncontrollable the vehicle.

Longitudinal Friction Variations

In the longitudinal direction variations in the friction properties of pavement surfaces occur more frequently than is commonly assumed. There are several types of such discontinuities. One type exists where one construction project adjoins another or where a surface has been repaired. In these cases the transition from one pavement to the other is often quite sharp, and usually it is recognizable by drivers. Whether drivers can and do judge correctly the related changes in friction properties, or even realize the possible existence of such changes, is debatable, as is whether they adjust their driving pattern to perceived changes. Because not all existing changes are perceived and, even if they are, likely to be judged incorrectly or ignored, they can constitute a potential hazard.

Gradual transitions occur at locations where the friction demand is higher than elsewhere along a roadway, as on curves and where acceleration and deceleration occur frequently and consistently. At these locations available friction tends to be lower than on the adjacent tangents with freely flowing constant speed traffic. The friction properties of the surface are degraded by the greater rate of pavement wear and polishing that accompanies speed changes and cornering. The friction needed for these vehicle maneuvers might be available elsewhere on the same pavement, but at the maneuver sites it may eventually decrease below that demanded by a significant number of drivers. The problem of measuring skid resistance on curves has been addressed only recently (4); thus no data are available for assessing the magnitude of the hazard at this and other maneuver sites. It is, however, well established that certain types of surface courses suffer considerable loss of friction potential under the influence of traffic, and that this loss is accelerated when the tires do more than normal amounts of scrubbing (5).

Short sections that have quite different friction properties than the adjoining pavement result from pavement markings, particularly at pedestrian crossings or where spot repairs have been made that extend across a traffic lane. In the first example the available friction is likely to be lower than that of the basic pavement, and in the second example it is likely to be higher than that of the basic pavement. Normally this is of little consequence, but it can present a hazard if an emergency maneuver must be executed at this location. The consequences will be much the same as if the front and rear brakes on a vehicle are out of balance, except that the friction imbalance is of a short duration only. The driver would have to react to two changes superimposed on an emergency maneuver, and this is at best within the capability of only the most skilled driver.

Remedies for some of the described cases of longitudinal friction variations are available. For instance, instead of repairing a few feet of pavement on a curve, overlaying the entire curve will prevent drivers from unexpectedly encountering a different friction level at a critical point. Overlaying a curve in its entirety raises the available friction on the curve, if only temporarily, above that of the adjacent tangents. This is desirable and will be cost effective if the curve was a high accident location even before the pavement needed repair. On the other hand, it is difficult to prevent variations between adjoining projects. If highly skid- and polish-resistant surface courses could be used everywhere, this will not only reduce the total number of skidding accidents, but the difference in accident experience between old and new projects will be reduced. This is so because, as is generally thought, the relationship of skidding accident rate versus skid resistance is flatter at higher skid numbers than it is at low ones (6). Alternately, if surfacing projects were designed to involve long sections of roadway, the number of changes in available friction would be reduced. Because drivers appear to go through a learning period whenever they encounter a change in driving environment, uniform sections of greater length may result in disproportionately greater improvements in accident rates than might be expected from the reduction in the number of abrupt changes in surface properties.

Many aspects of the problem of longitudinal variations of friction have not been investigated. There are no applicable statistics, but the following example illustrates the potential hazard that traveling from a high friction surface to one with much poorer friction properties can present. When the latter is of such design that the combination of summer heat and heavy truck traffic pumps the asphalt to the surface of the pavement, the wheel paths get quite slippery. Bleeding pavements can have an SN_{40} as low as 10 (see Figure 3). If such a section is encountered on an upgrade by a vehicle coming from a surface with an SN_{40} of 40, running under full power, the drive wheels may suddenly begin to spin unless the driver anticipates the change and reduces power. The transition zone may be no more than 10 ft long, and in some cases less. At 55 mph it takes 0.12 sec for the vehicle to travel the 10 ft, which does not give the driver enough time to sense the impending wheel spin and prevent it. The consequence can be a serious deviation from the intended path. Vehicle spin-out may occur. Similar hazards exist during braking and cornering or whenever the wheels of a vehicle suddenly encounter a drop in available friction. In the reverse case, other instabilities occur that can catch an inattentive or inexperienced driver off guard.

Thus, from the viewpoint of safety, there is little doubt that longitudinal variations in pavement properties should be avoided where possible and, if this cannot be done, these variations should be held to a minimum. Where major variations exist, warning signs may be an appropriate measure until surface conditions can be corrected.

FIGURE 3 Extreme variation in friction (skid number of the advance pavement is 70, and skid number where the wheel paths have flushed is less than 10).

Pavement Markings

Pavement markings are primarily used to provide visual guidance for drivers and to guide traffic flow. Turn arrows, hazard warning messages, and so forth are frequently marked directly on the pavement surface. In their intended roles pavement markings are universally held to provide positive benefits, particularly under conditions of poor visibility (7,8), but the degree of skid resistance that they provide is of increasing concern with the growing use of plastic materials and heavy marking in sections such as ramps and gores. Marking materials generally lower the skid resistance of a pavement and, when applied over large sections, increase wet skid stopping distances. Differential friction caused by the application of marking materials also gives rise to such hazardous conditions as excessive vehicle yaw during locked-wheel skids, loss of control during motorcycle or bicycle turning and braking maneuvers, and slipping and falling by pedestrians on crossings.

Skid-resistance requirements for marking materials have traditionally been specified in terms of low-speed wet friction measurements (7). However, high-speed skid resistance measurements recently made by the Massachusetts and Michigan departments of transportation (9,10) have demonstrated that low-speed measurements do not accurately reflect the absolute skid resistance of marking materials for vehicles traveling at highway speeds. Results for three materials field-tested in the Michigan study were as follows:

Material	SN_{40}	BPN
Fast-drying white paint (with beads)	37	31
Extruded hot plastic (with beads)	23	35
Smooth cold plastic (no beads)	4	14
Bare pavement substrate surface	67	-

In this table SN_{40} is the skid number at 40 mph as measured by ASTM E274 method of test, and BPN is the British pendulum number as measured by ASTM E303 method of test. Two of the three materials had lower SN_{40} than BPN, with the unbeaded plastic having a friction level consistent with hydroplaning.

In a later, more comprehensive study (11), the performance of 11 different materials applied to four different pavement surfaces was evaluated. A total of 113 combinations of material type, material formulation, and pavement surface were included in the study. Macrotexture, SN_{40}, and BPN measurements were made on each sample surface. Predictor equations relating SN_{40} to BPN and root mean square (RMS) macrotexture height were then developed by linear-regression techniques. A single regression equation, which would encompass all of the materials, could not be formulated at an acceptable level of correlation, so the materials were grouped into eight categories, and a separate equation was developed for each category. Thus the results of the study may be used to estimate the high-speed skid resistance of typical marking materials from low-speed laboratory measurements. In most cases a BPN measurement is sufficient to provide the SN_{40} estimate, although the addition of a macrotexture measurement may be beneficial in improving the correlation. The average skid resistance numbers measured on the various materials included in the study are given in Table 1 (11).

TABLE 1 Average High-Speed Skid Resistance of Five Marking Materials *(11)*

Marking Material	No. of Applications	Avg Skid Resistance ($\overline{SN}_{40}$)	Standard Deviation
Traffic paint (unbeaded)	22	20.7	8.0
Traffic paint (beaded)	41	26.7	6.8
Thermoplastic (unbeaded)	12	18.7	10.1
Thermoplastic (beaded)	26	24.7	7.5
Preformed plastic	11	25.2	8.7

Specific findings of the study were as follows.

1. For all combinations of material, formulation, and pavement surface, the high-speed skid resistance of the marking material was lower than that of the bare substrate pavement surface, whereas the low-speed skid resistance in some cases was higher than that of the substrate.
2. The skid resistance of markings applied in the field did not increase significantly with time and suffered seasonal and short-term variations similar to those of the substrate pavement surface.
3. Beaded paint and plastic marking materials had significantly higher skid resistance than unbeaded materials. The use of unbeaded materials should be avoided.
4. Chlorinated rubber-based paints had significantly lower skid resistance than alkyd resin paints.
5. Spray thermoplastics had higher skid resistance than hot-extruded thermoplastics.

The effects of differential friction caused by marking materials on highway safety is difficult to determine because of a lack of accident studies specifically directed toward the problem. However, single- and double-delineation stripes do not appear to be hazardous to the operation of cars and trucks (11). When a large section of marking material is present on wet pavement, a differential friction problem could exist. In a computer simulation study of cars skidding on pavements with differential friction caused by marking materials (11), a design procedure was developed for determining the maximum allowable differential friction between pavement and material, given the length of the marking on the pavement. Boundaries of safe operation are shown in Figure 2, the same figure that gave boundaries for transverse friction variations. Safe operation is indicated if a given combination of the lower coefficient of friction (μ_2) and if the length of differential friction surface falls to the right of the appropriate μ_1 curve; otherwise braking is potentially unsafe.

The criteria for safe operation were somewhat difficult to quantify, but they were based on the following observations of vehicle behavior when drift angle was large (drift angle is the angle between the forward and resultant velocity vectors at the center of gravity of a vehicle). If a vehicle is executing a yawed skidding maneuver with locked wheels and the wheels suddenly unlocked, then (a) the driver has no steering control over the vehicle if the drift angle is approximately equal to or greater than 20 degrees or (b) the vehicle will tend to travel along the line of its longitudinal axis if the drift angle is less than approximately 20 degrees (assuming no control action by the driver). Under the latter circumstance the rate at which the vehicle will travel laterally across the pavement can be approximated by the product of vehicle speed and drift angle ($U\beta$). If ($U\beta$) = 12 ft/sec, the vehicle will move laterally one complete lane width in 1 sec.

Justification for the criteria is along the same general lines used by Burns (2) to identify boundaries of safe operation on surfaces with differential friction, although a direct comparison between the criteria shown in Figure 2 and Burns' criteria is difficult to make.

Pavement markings present a wet skidding hazard to operators of motorcycles and bicycles. However, the extent of the hazard and its overall impact on highway safety cannot be determined at present, particularly in view of the acknowledged, but obviously positive, benefits of pavement marking materials.

Pedestrian safety is another concern at crossings in urban areas. Requirements for satisfactory walking traction are a static coefficient of friction of 0.5 or higher and a sliding coefficient of friction higher than the static value (12). The walking traction performance of marking materials in current use appears to be satisfactory, or at least (for materials with the most unsatisfactory performance) no worse than borderline.

Steel Grid Flooring

Steel grates for bridge riding surfaces are rarely constructed today, even though the current AASHTO bridge specifications (13) contain sections governing their use. An earlier edition (14), published in 1961, refers to the friction available on these surfaces with the following statement: "The upper edges of all members forming the wearing surface of an open type grid surface should be fabricated or treated to give the maximum skid resistance." What the maximum skid resistance should be, quantitatively, is not specified. This statement remains unchanged in the current AASHTO bridge specifications.

In 1951, the TRB Committee on Surface Properties Related to Vehicle Performance, under the chairmanship of R.A. Moyer, published a graph showing the coefficients of friction available on an open grid steel bridge deck as a function of speed (15). This graph [Figure 4 (15)] shows the coefficient of friction for a new tire made of synthetic rubber varying from 0.4 at 11 mph down to 0.25 at 40 mph.

In response to several loss-of-control events on a Louisiana bridge in the late 1970s, an investigation was undertaken to determine if the steel grid deck was a contributing factor. ASTM E274 skid numbers were determined on the bridge at several different positions. Although the bridge deck was more than 30 years old and polishing of the steel was apparent in the wheel paths, the values of the skid numbers were not exceptionally low, varying from 25 to 38. These values compare favorably with those reported by Moyer more than 30 years ago. It was concluded that the problem was more likely caused by the susceptibility of the deck to icing, rather than by low values of wet friction.

In all probability steel grid decks are subject to the same concerns discussed under longitudinal

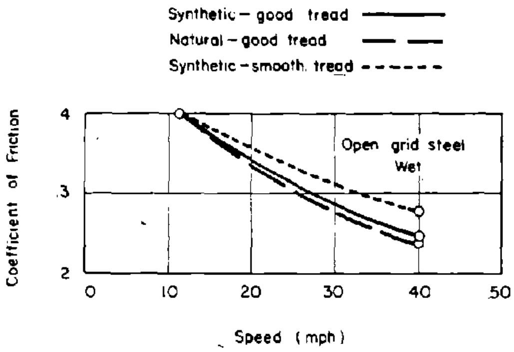


FIGURE 4 Effect of different type tires on skid resistance for wet open-grid steel bridge floors *(15)*.

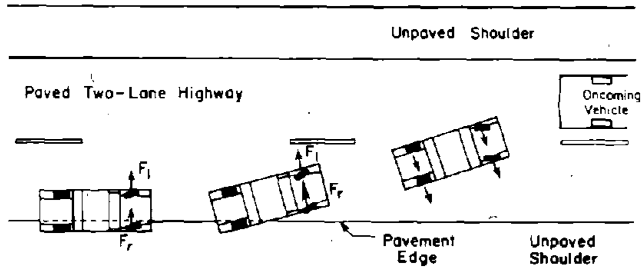
and transverse friction variations, because they normally occur on old bridges where wheel path polishing is pronounced. They also are more susceptible to icing because the steel should lose heat much faster than a portland cement concrete deck. This problem relates to the excessively low friction available on icy surfaces, which will be discussed further in a subsequent chapter.

Traveled Surface to Shoulder

The problem of friction variation between the paved surface and the shoulder is related to the lateral variation influence. Although it is such a special influence and such a relatively common (and critical) influence, it will be given special treatment.

The primary focus here concerns the existence of a lower friction surface on the shoulder immediately adjacent to a traveled lane. There are accidents each year that are triggered by a single vehicle loss of control resulting from the inability of some drivers to deal with a lower friction shoulder surface. A driver, either through inattention or from some external influence, allows his vehicle to run off the paved surface, perhaps only a foot or two, so that the wheels, at least on one side of the vehicle, are on an unpaved, lower-friction surface. It may be sand, loose gravel, soil, or perhaps a muddy wet surface. The next reaction of the driver, as he becomes conscious of the situation, is critical. If the driver reacts with restraint, allowing the vehicle to slow while using modest steering inputs, the paved surface can be easily and safely regained. All too often, however, this is not the case. The driver reacts quickly with a steering input that is too large. The result is a precipitous steer force generated when the offside front wheel regains the paved surface. These actions may result in a collision with another vehicle or a roll. Figure 5 illustrates this phenomenon.

In Figure 5a the vehicle is shown with the right wheels on the shoulder (lower friction) surface just after the driver has made a left steer input that is too intense. The steering may even feel appropriate to the driver in terms of the rate at which he is regaining the appropriate lane of the roadway. The driver is not prepared, however, for the radical increase in the cornering force and thus the rate of cornering when the right front tire comes in contact with the higher friction lane surface, as shown in Figure 5b. The result is a vehicle fundamentally



(a) Right side wheels on shoulder. Driver overcorrects due to suprise and/or low value of F_r. ($F_r < F_l$)

(b) Right front wheel encounters pave surface. Covering force or right front wheel F_r increase precipitiously. ($F_r > F_l$)

(c) Driver corrects steering to the right but not fast enough to avoid penetrating opposite traffic lane.

FIGURE 5 Illustration of loss of control caused by oversteering on low-friction shoulder.

out of control, as shown in Figure 5c. Here the vehicle goes into adjacent lanes, may even go completely across the highway, or may spin out, possibly resulting in a vehicle roll. The high lateral acceleration produced in the case shown further complicates the recovery problem for an unbelted driver on a bench front seat. This driver may be thrown completely out of the wheel position, precluding any further efforts of value in regaining control. Figure 6 shows the results of an accident due to the oversteering phenomenon.

FIGURE 6 Honda CVCC after spinning into the path of a larger vehicle.

One aspect of this phenomenon is that the existence of even extremely modest pavement edge height differentials, even 1 in. or less, may be blamed for the loss of control. The chapter on Pavement Edges (Chapter 4) illustrates the insignificance of these low values of edge differentials on loss of control. The degree to which a lower friction surface on the shoulder may influence safety is a function of the exposure to people allowing vehicles off the paved surface, perhaps related to geometrics (16), and to the degree to which the shoulder surface friction is lower than that of the paved surface. The available friction of paved surfaces both dry and wet is widely known. A major treatise on this subject is given by Kummer and Meyer (17). Data concerning available friction levels on surfaces covered by sand, gravel, soil, and mud are much more limited.

It appears there was much more interest in this type of surface when paved roads were rarer. Data

TABLE 2 Sites Measured for Differential Skid Numbers

Site	Pavement	Shoulder or Adjacent Surface	Surface	Condition[a]	Run 1	Run 2	Run 3	Mean Skid No.
1	Bituminous concrete	Crushed limestone gravel, 5-25 mm; some asphalt overspray	Pavement	D	87.4	87.3	86.1	85.9
			Pavement	W	34.6	39.8	34.3	36.2
			Shoulder	D	75.6	81.4	77.1	78.0
			Shoulder	W	72.5	72.7	74.5	73.2
2	Seal coat, asphalt bleed; heavy truck distress (tread impressions)	Poorly graded gravel from 20 mm to silt	Pavement	D	38.4	37.1	41.2	38.9
			Pavement	W	22.6	12.3	13.9	16.3
			Shoulder	D	61.3	61.7	62.8	61.9
			Shoulder	W	56.3	57.5	59.7	57.8
			Shoulder	W*	40.3	56.5	49.8	48.8
3	Prepared fill (roadway under construction)	Gravel, sand, and clay mixture	Pavement	D	69.7	71.7	74.1	71.8
			Pavement	W	56.3	50.9	53.1	53.4
			Shoulder	D	69.8	68.1	67.4	68.4
			Shoulder	W	59.9	63.4	61.6	61.5
4	Bituminous concrete, some asphalt bleed	Gravelly sand	Pavement	D	44.2	42.3	39.5	42.0
			Pavement	W	23.8	33.7	26.6	28.0
			Shoulder	D	61.6	59.8	60.2	60.5
			Shoulder	W	59.7	60.5	61.3	60.5
5	Bituminous concrete; weathered, somewhat raveled	Silty sand, course gravel, some spillover bituminous concrete and vegetation	Pavement	D	45.5	46.1	46.5	46.0
			Pavement	W	39.3	41.4	39.6	40.1
			Shoulder	D	59.6	60.1	63.9	61.2
			Shoulder	W	58.7	59.6	62.5	60.3
6	Seal coat, asphalt bleed	Peat with some gravel, vegetation	Pavement	D	45.7	44.2	41.3	43.7
			Pavement	W	22.8	24.2	24.3	23.8
			Shoulder	D	57.9	59.6	62.3	59.9
			Shoulder	W	44.8	32.8	31.7	36.4
			Shoulder	W*	25.5	22.1	19.3	22.3
7	Concrete	Silty gravel	Pavement	D	68.5	–	–	68.5
			Pavement	W	42.4	–	–	42.4
			Shoulder	D	63.0	61.7	62.4	62.4
			Shoulder	W	56.6	55.7	51.8	54.7
			Shoulder	W*	31.0	29.0	–	30.0

[a]Note that D = dry, W = wet, and W* = wet after significant natural rainfall.

on the values of available friction on mud, soil, gravel, sand, and sod are given in Chapter 7. These values can range from as low as 0.2 to more than 1.0. The lowest values are found on wet clay and on wet grass. Some gravels exhibit surprisingly high values in either wet or dry conditions.

The most recent work has been provided by R.J. Koppa (Pavement Edge, Roadway Discontinuities, and Vehicle Stability, unpublished Task Report on Project 328, Texas Transportation Institute, October 1982). By using an ASTM E274 locked-wheel skid trailer, Koppa measured both the locked-wheel friction on unpaved shoulder surfaces and the friction on the pavement immediately adjacent to the shoulder. The difference in friction, as indicated by locked-wheel braking, was thus directly observed. The data in Table 2 describe the surface types and the results of Koppa's tests. In the fourth column, labeled Condition, the pavement condition is given [note that D = dry, W = wet (ASTM internal watering system), and W* = wet (by significant natural rainfall)]. Only on sites 2, 6, and 7 were skid numbers determined after significant natural rainfall, a condition more critical than the quick coating provided by the internal watering system. The results on site 2 were somewhat surprising in that the dry skid number on the pavement was lower than the wet skid number on the shoulder (38.9 for pavement dry compared with 48.8 for shoulder wet).

A real contrast in relative values would be when both surfaces are wet: pavement wet (SN = 16.3) and shoulder slightly wet (SN = 57.8). This would not produce the control sequence described in Figure 2, but it could produce a problem if a rapid return was produced that resulted in a spin-out due to the low available friction on the pavement.

On sites 6 and 7 the results were more as expected. Assuming the pavement surface dries more rapidly than the adjacent shoulder, the critical situation would be when the pavement surface has just dried and the shoulder is still wet: 43.7 compared with 22.3 on site 6, and 68.5 compared with 30.0 on site 7.

In general, the friction values obtained on the gravel shoulders were rather high, which indicates good traction. The real problems would be expected on wet soil with a high clay content and where wet vegetation contributed to lowering available friction. On surfaces of this type little is known about the relationship between available cornering friction and braking friction. In this case it is the cornering friction that is critical, and few observations of this type are available. Braking skid numbers may not provide satisfactory estimates.

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CHAPTER 6 Water Accumulations

Don L. Ivey and John M. Mounce

Hydroplaning and Hydrodynamic Drag

Published opinions concerning hydroplaning and highway safety vary. At one extreme it is contended that hydroplaning has no significant influence on accidents under typical operating conditions. The other extreme maintains that hydroplaning has a great influence on wet weather accidents. Each of these opinions may be correct at specific highway sites. In general, the truth may lie somewhere between these extremes. Hydroplaning is a low-probability event, primarily because the high-intensity rainfalls necessary to flood a pavement are low-probability events. Hydroplaning, however, is so hazardous that when it does occur, criteria for surface design to reduce the probability of hydroplaning are warranted.

Some of the earliest investigations and technical reports on hydroplaning came from the National Advisory Committee for Aeronautics (NACA) and its successor the National Aeronautics and Space Administration (NASA); these reports were primarily concerned with hydroplaning of aircraft during landings. In this connection the U.S. Army Air Corps and its successor the U.S. Air Force also did valuable work. Later the Road Research Laboratory in Great Britain began investigations related to automobiles. Concurrent with this research, Americans and Germans studied tires and road surfaces to seek their own answers. More recently, the Highway Research Board, now the Transportation Research Board, the National Cooperative Highway Research Program, and the FHWA have encouraged and are financing studies related to tire-pavement interaction and hydroplaning, studies that are bringing the state of the art to a respectable level.

Hydroplaning is the separation of the tire from the road surface by a layer of fluid. On a microscopic scale, operational conditions may involve some degree of partial hydroplaning as long as there is significant water present. On a macroscopic scale, however, this zone can be defined as occurring during those operational conditions when there is some significant degree of penetration of a water wedge between the tire and pavement contact area.

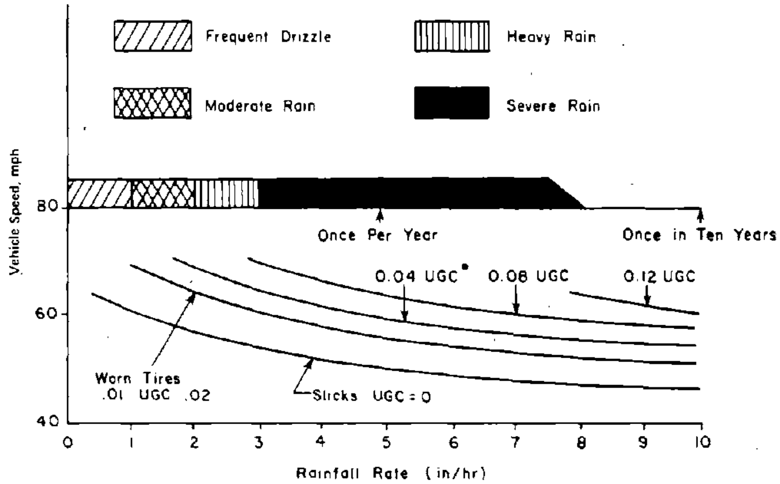
Hydroplaning of pneumatic-tired vehicles has been divided into three categories by Horne (1): viscous hydroplaning, dynamic hydroplaning, and tire-tread rubber-reversion hydroplaning. Viscous and dynamic hydroplaning are the important types of hydroplaning encountered by passenger cars. Tire-tread-reversion hydroplaning occurs only when heavy vehicles such as trucks or airplanes lock their wheels while moving at high speeds on wet pavement, with macrotexture but little microtexture. Viscous hydroplaning may occur at any speed and with extremely thin films of water. Browne (2) states that viscous hydroplaning occurs only on surfaces where there is little microtexture. A thin film of water remains between the tire and pavement because there is insufficient pavement microtexture to promote the breakdown of the water film.

Dynamic hydroplaning occurs when there is insufficient time to clear the water from between the tire and the pavement in the tire footprint. An excellent summary of the relationship among vehicle speed, tread condition, and water depth (as a function of rainfall intensity and pavement cross slope) is given by Yeager (3); see Figure 1 (3). It should be noted that this predictive method is limited to the two combinations tested and does not apply to combinations of cross slope, pavement texture, and drainage-path length. For a comprehensive treatment of all factors related to dynamic hydroplaning, the reader should refer to the recent work of Gallaway et al. (4).

Figure 1 shows that dynamic hydroplaning can occur with water depths as little as 0.03 in. with slick tires. Under carefully controlled laboratory conditions, Gengenbach (5) identified dynamic hydroplaning with water depths as small as 0.01 in. Gengenbach was testing under ideal laboratory conditions. Observations of hydroplaning on pavements would not be expected at this water depth. When significant lengths of standing water are encountered on a pavement, hydroplaning can cause loss of vehicle control. Figure 2 shows the result of excessive speed and flooded wheel paths.

Observations of hydroplaning as a test trailer passed over or through a puddle showed that hydroplaning could occur with puddle lengths as short as 30 ft. The hydroplaning, or hydrodynamic loss of traction, over short puddles does not have a significant influence on safety.

However, hydrodynamic drag during the traversal



Water depth (in)						
	0.030	0.057	0.075	0.088	0.097	2.1% Slope, 11 ft. Drainage Length
	0.045	0.072	0.092	0.110	0.124	1.56% Slope, 22 ft. Drainage Length

FIGURE 1 Estimated free rolling minimum full dynamic hydroplaning speed for passenger tires (conditions: relatively smooth surface, rounded footprint, and rated inflations and loads) *(3)*.

FIGURE 2 Result of excess speed and dynamic hydroplaning on flooded wheel paths.

of a road puddle in combination with loss of traction does have an influence. Gengenbach (5) demonstrated that a drag as high as 25 lb could occur in as little as 0.078 in. of water, and he believed that it was not further increased by deeper water layers.

These were steady-state drum tests, however, and much higher values were observed by Gallaway in typical roadway puddles. Gallaway found peak hydrodynamic forces encountered by a tire during puddle traversal to range from 70 to 330 lb. One of these test puddles is shown in Figure 3. Hydroplaning, as indicated by loss of traction, occurred at speeds between 40 and 50 mph. If a peak longitudinal drag force were applied to one vehicle front wheel only, it could have a significant destablizing effect. Such an event might occur in a situation in which water collects along a curb because of poor drainage. The opposite effects of hydroplaning and hydrodynamic drag require some elaboration. Although full hydroplaning destroys any capability of the tire to interact with the pavement surface, and thus no capability to provide directional stability, hydrodynamic drag does place a force on the tire surface that provides a resistance to movement, in effect a relatively small stopping traction force.

FIGURE 3 Puddles used in short-duration hydroplaning tests.

To obtain a rough estimate of the potential real-world effect, some simple computations were made by using a hypothetical vehicle weighing about 3,800 lb with a wheel base of 112 in. and a track width of 60 in. A conventional American automobile of this size would have a vertical load on each front wheel of about 1,000 lb. If the inertial effects were neglected and the torque produced about the center of gravity was calculated, it would take a corresponding opposing torque to maintain directional stability. Assuming that the opposite front wheel was on pavement that was only wetted, with no standing water, this opposing torque could be applied by developing a cornering slip angle by steering. Data for a typical tire on wetted pavement indicate that a front wheel slip angle of about 2 degrees would be required. For a typical steer ratio of about 20:1, this would require a steering wheel correction of about 40 degrees. If such a correction was made, and full pavement contact was suddenly regained, it could cause movement toward the opposing traffic lane before appropriate steering correction is possible.

In the case in which both front wheels are fully hydroplaning, but there is variation in water depth laterally, the unequal drag forces could cause yaw instability with little or no corrective steering capability available. There is little doubt, considering these illustrations, that the drag forces generated by positive water depths could pose a hazard to some drivers.

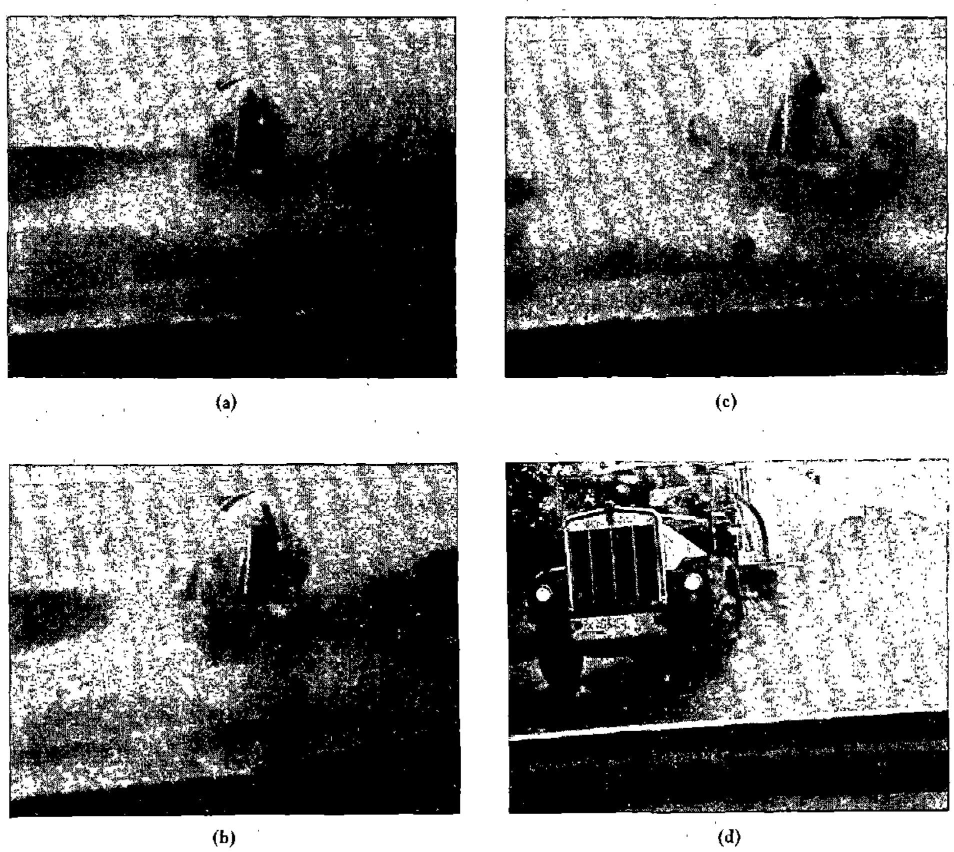
Visibility

Research indicates that accident rates increase with the amount of rainfall in a roughly linear fashion. This effect was demonstrated by Ivey et al. (6) in 1977 and further substantiated by Sherretz and Farhar (7) in 1978. These findings were based on National Safety Council accident data and National Oceanic and Atmospheric Administration climatological data.

One factor that influences wet weather accident rates is the decrease in visibility caused by splash and spray. Kamm and Wray (8) state that, "passing a vehicle on a wet road requires a level of skill much higher than needed in most phases of driving. The maneuver is considerably more difficult when the driver's view is obscured by spray thrown up by the rear wheels of the adjacent vehicle." The phenomenon of splash and spray was described by Weir (9) as follows: "Splash tends to be relatively large droplets which move in ballistic trajectories and are associated with deep water or low speeds. Spray is composed of the smaller droplets, which tend to be suspended in the air and are associated with shallow water or high speeds. Formation requires a source of moisture, a hard or smooth surface, and some velocity of both vehicular movement and/or flow of air."

The degradation of visibility caused by splash and spray can be severe under dense traffic conditions when wipers do not clear the windshield effectively. The problem is described as follows (10): "Splash and spray create more or less a permanent smear which will be present on the glass, making it more difficult to see dim objects to the front of the car. Light emitted from headlights of opposing vehicles is refracted irregularly such that objects at some distance in front of the car will be considerably distorted in shape creating difficulties in recognition and judgment leading to unsafe operations."

There are many factors that interact to determine the extent and effect of splash and spray produced by water accumulations on pavement. Figure 4 illustrates the effect of splash and spray on visibility from behind a large truck. Much study has concen-



(a) (c) (b) (d)

FIGURE 4 Sequence of photos taken following a truck in the rain, illustrating poor visivility caused by splash and spray: a-c show overtaking, and d shows pass completed.

trated on tire design to remove as much water as possible from the tire-roadway contact area; however, this has only led to poorer visibility as more water is expelled to the sides and rear of the tire.

Three significant research efforts have addressed the issue of splash-and-spray reduction by pavement design. Maycock (11) conducted studies on six bituminous surfaces--four were impervious, one slightly pervious, and one very pervious (porous). The surface dressings performed slightly better than the smoother asphaltic surfaces, whereas the very porous macadam surface performed extremely well.

Brown (12) investigated six experimental open-textured bituminous-macadam pervious surfaces with nominal top-sized aggregates ranging from 0.40 to 0.75 in. All experimental surfaces performed well in reducing spray and retained their spray-reducing properties after being subjected to heavy traffic for almost 2 years. Simoncelli (13) studied open-graded bituminous mixtures developed in many countries, especially in the United Kingdom and Scandinavia. These surfaces have proved highly successful in reducing spray, improving visibility in rain, and enhancing the safety of the driver. The positive influence of open-graded surface spray reduction was most recently demonstrated by Gallaway et al. (4). This reduction is illustrated by Figure 5 (4).

Splash and spray can degrade driver visibility and safety. Low places in the pavement surface that hold water or flat spots that drain poorly contribute to the splash-and-spray problem. Increasing surface texture or providing porous self-draining pavements in favorable climates can contribute to better visibility. Maintaining these surfaces may prove to be difficult. Surface texture is smoothed by traffic, which may also consolidate porous pavements. Some fender systems for trucks have been devised to reduce splash and spray, but they are costly and create operational problems. Side skirts and spray-suppressant mud flaps are steps in the right direction. However, until a major breakthrough in one of these occurs, the driver must use extreme caution when environmental conditions result in reductions in visibility.

FIGURE 5 Contrast between spray caused by vehicles *(4)*—top: open-textured (porous) surface; bottom: conventional (nonporous) surface.

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CHAPTER 7 Surface Contaminants

E. A. Whitehurst and Don L. Ivey

Ice and Snow

The problems of vehicle performance on highways covered by ice or snow have been studied for many years by a number of organizations. Much of the work has been done by tire manufacturers, and much of this work is proprietary and, to a large extent, unpublished. Limited investigations have been made by several universities and other research agencies. Probably the largest volume of published data is available in the annual reports of the National Safety Council Committee on Winter Driving Hazards, which, during most winters since 1939, has conducted a 2-week test program of vehicle performance on ice and snow. In these test programs the Committee has been supported with equipment and personnel by vehicle manufacturers, tire manufacturers, trade associations, individual trucking companies, federal and state regulatory agencies, and universities. Results of these many test programs have been published in the annual reports of the Committee, and most of the observations included herein are based on the Committee's findings.

Although front-wheel-drive automobiles have become increasingly popular in the United States during the past few years, relatively few tests of their performance on ice- and snow-covered surfaces have been conducted. In the following discussion all references to automobile performance are based on tests of rear-wheel-drive automobiles, unless specifically designated otherwise.

In any consideration of ice and snow as a surface contaminant, attention must be given to the manner in which ice and snow differ from other roadway surface contaminants. Three such differences should be fully understood.

The fist consideration is that of loss of traction. Although many roadway surface contaminants result in a loss of traction, the magnitude of the loss experienced when traveling on packed snow or ice probably exceeds that of most other contaminants. Dry pavements may exhibit skid numbers as low as 25 and still provide adequate surfaces for normal traffic operations where traction demands are modest. When the surface is covered with ice and the temperature is near the freezing point, the skid number will be on the order of 5 to 7. Thus the capability of the vehicle to move, corner, and stop is tremendously reduced.

The second consideration is that of temperature effect. In most cases variations in temperature do not result in large changes in the traction available at the tire-pavement interface. It has been reported that in normal wet skid testing, wet skid number variations of 1 to 2 skid numbers per 10°F temperature change occur. Such changes would rarely be noticed by a vehicle operator. In the case of traction on an ice-covered surface, however, the available traction, although always low, changes drastically with temperature relative to the general level of available traction. The colder the ice on which the vehicle is traveling, the greater are the traction capabilities of the vehicle. In fact, in extremely cold weather, when the ice surface temperature is approximately 0°F, the traction level of the surface will be more than twice that of a surface on which the ice is just at the freezing point. The driver is operating under the greatest hazard when the ice is barely adhering to the pavement surface.

The third consideration is that of the effect of vehicle gross weight. The classical relationship between vehicle speed and locked-wheel sliding distance indicates that the weight of the vehicle is not a factor. This has been shown experimentally to be true for vehicles traveling on dry pavements, and even to be true (within experimental error) for vehicles of different weights traveling on wet surfaces, as long as the tire compound for the tires on the two vehicles is the same and the tread configurations are the same or nearly so. On ice, however, it is not true. The heavier vehicle will require a greater distance in locked-wheel stopping from a given speed than will the lighter vehicle. In tests conducted by the Committee on Winter Driving Hazards involving locked-wheel stops from an initial speed of 20 mph on ice and at an ice surface temperature of 25°F, stopping distances averaged 247 ft for a 16,500-lb truck, 257 ft for a 28,360-lb truck, and 333 ft for a 70,880-lb tractor trailer combination (1). During the same test program the average locked-wheel stopping distance of a passenger vehicle from 20 mph on ice at 25°F was 154 ft. Thus the heavily loaded tractor trailer required more than twice the locked-wheel stopping distance of the passenger vehicle. It is not completely clear that the weight was the only influence here. Differences in braking systems of the different trucks are a complicating factor. Similiar relationships for vehicles on wet pavement have been reported by Dijks (2).

The reason for this phenomenon is not currently understood. It has been hypothesized that some melting always occurs under the wheels of a vehicle sliding on ice and that the vehicle is, therefore, always sliding on wet ice. This hypothesis suggests that more melting would occur under wheels with higher contact pressures than under those with lower contact pressures. In this case the heavier vehicle would be sliding on wetter ice and would, hence, require a longer distance to stop from a given speed.

Vehicle performance tests may be conducted reliably on prepared ice surfaces, and a substantial body of data based on such tests is available. It is much more difficult to conduct reliable vehicle performance tests on snow-covered surfaces, and the available data based on such tests are far less satisfactory--in terms of both volume and reliability--than that based on ice tests. Vehicle performance tests on snow-covered surfaces are affected by such parameters as the depth of the snow, its moisture content, its density, and the degree to which it has been compacted under traffic. It may be stated that, in general, snow that has been compacted under traffic for several hours subsequent to a snowfall will be rough but will have essentially the tractive capacity of ice. In loose snow, although the tractive capabilities will always be low, they are affected by plowing in front of the wheels, which will improve stopping characteristics but degrade pulling characteristics; and in some cases it may improve, and in others degrade, cornering characteristics.

The capability of a vehicle to move on surfaces covered with ice or snow is drastically reduced. It is not uncommon on glare ice near the freezing temperature for a vehicle that has come to a stop and set for just a few moments to be unable to develop sufficient traction to move forward again without help from an outside source. Much attention has been given, therefore, to the evaluation of devices to improve vehicle performance in pulling traction under such adverse conditions.

The results of many years of testing by the Committee on Winter Driving Hazards are summarized in charts in a current National Safety Council publication entitled, "Hot Tips for Cold Weather Drivers." The data reported therein indicate that the use of snow tires on the rear wheels will improve pulling traction on glare ice at 25°F by about 28 percent. The use of studded snow tires on the rear wheels, where the studs are controlled-protrusion tungsten carbide steel studs, installed in a pattern involving something on the order of 80 studs per tire, will improve pulling traction under the same conditions by about 218 percent. Greatest improvement is attained through the use of reinforced tire chains on the rear wheels, which improves pulling traction by about 630 percent.

A number of varieties of chains for passenger vehicles are currently available. The performance of all of them for which test data are available falls below that of the reinforced tire chain, and they rate generally in the order in which their aggressiveness increases; that is, to be significantly effective in improving pulling traction on ice, they must significantly dig into and damage the ice surface.

Although some of the chains for which data are available provide significantly less improvement in performance on ice than do the reinforced tire chains, they may have some distinct advantages that appeal to motorists. Some of the less-effective chains are considerably easier to install on the wheels of the vehicle than are the heavier reinforced tire chains, and some chains effectively resist destructive wear while in use on wheels traveling over a bare pavement better than do the reinforced tire chains.

On loosely packed snow, an ill-defined term generally involving a hard-packed snow base with several inches of looser snow on top, snow tires improve pulling traction over regular tires by about 51 percent, and reinforced tire chains improve traction by about 313 percent.

Although the ability to get a vehicle into motion and to keep it traveling in controlled motion is highly important, most studies of vehicle performance on ice- and snow-covered surfaces have dealt with the ability to stop.

The National Safety Council publication previously cited ("Hot Tips") summarizes a number of years of tests to indicate that on glare ice at 25°F the locked-wheel stopping distance for a passenger vehicle equipped with conventional highway tread tires averages 150 ft. When snow tires are used on the rear wheels of the vehicle, the distance is about the same. Repeated tests have indicated that in stopping on ice, snow tires provide no advantage, usually performing essentially the same as or slightly (1 to 5 percent) poorer than conventional highway tread tires. The use of studded snow tires (involving studs of the type and configuration previously described) on the rear wheels reduces the stopping distance to approximately 120 ft, an improvement of 19 percent. The use of reinforced tire chains on the rear wheels reduces the average stopping distance to 75 ft, an improvement of 50 percent.

On loosely packed snow a passenger vehicle equipped with conventional highway tread tires stops in about 60 ft from 20 mph. The use of snow tires on the rear wheels provides some improvement under this condition--about 13 percent--and reduces the stopping distance, on average, to 52 ft. When reinforced tire chains are used on the rear wheels, the stopping distance is further reduced to 38 ft, an improvement of 37 percent.

In the foregoing discussion reference has been made to the use of studded snow tires only on the rear wheels of the vehicle. If such tires were used on all four wheels of the vehicle, an additional improvement in stopping distance should be expected. Limited tests have shown this to be the case (3). The practice of using studded tires on all four vehicle wheels is so uncommon in the United States, however, that few tests involving this configuration have been performed. Studded tires have not been found to be effective in either pulling traction or stopping traction on snow-covered surfaces until the snow reaches a degree of compaction at which its characteristics approximate those of ice.

Much attention has been given over the years to the development of appropriate braking techniques when operating a vehicle over ice-covered surfaces. For many years the advice given by the National Safety Council and others was to apply the brakes in a series of sharp applications and releases, a procedure generally referred to as pumping. The purpose of this procedure was to obtain deceleration through braking without reaching a sustained condition of brake lockup, thus retaining steering capability while braking was being accomplished. This advice is still sound if the operated vehicle is equipped with drum brakes.

Most modern automobiles, however, are now equipped with disc brakes on the front wheels. Disc brakes do not release as quickly as drum brakes, and if pumped rapidly they may not release at all, thus causing a condition of continuous lockup. For vehicles with disc brakes, the brakes should be squeezed with a slow, steady pressure until they are close to the point of lockup and maintained in that status. If lockup occurs the brakes should be released and, once the wheels are rolling again, the procedure should be repeated.

Reference was made earlier to the effect of vehicle gross weight on stopping distance. The importance of this phenomenon, particularly to the drivers of heavy vehicles, can hardly be overemphasized. Its importance to other investigators in the field is primarily to highlight the necessity for conducting all tests under a carefully controlled, constant temperature condition, which is frequently impossible, or of adjusting test results to a fixed temperature base before reaching conclusions or making comparisons. The relationship of locked-wheel stopping distance to ice surface temperature normalized to a temperature of 25°F, which was established by the Committee on Winter Driving Hazards on the basis of several years of effort, is shown in Figure 1. It is important to note that the Committee found this relationship to hold for vehicles ranging from 3,280 to 72,200 lb gross. The figure shows, for example, that at an ice temperature of approximately -2°F, the multiplier to relate to an ice temperature of 25°F is 2.00. Thus if a passenger vehicle requires 75 ft to slide to a stop from an initial speed of 20 mph at -2°F ice temperature, it will require 150 ft to make a similar stop when the ice temperature is 25°F. If a heavily loaded tractor trailer requires 150 ft to make such a stop at -2°F, it will require 300 ft to make the same stop at 25°F.

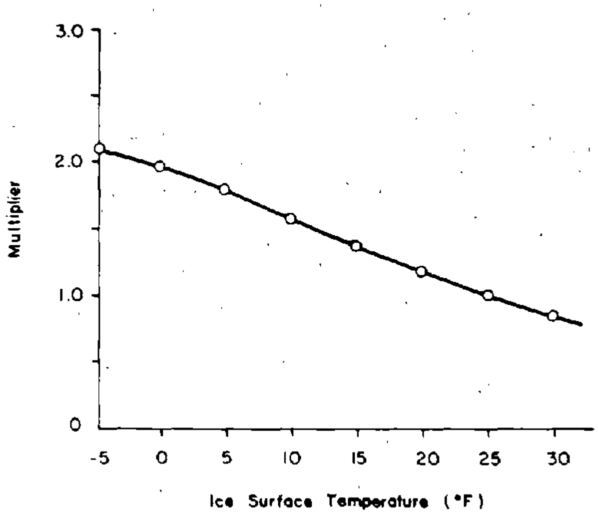

FIGURE 1 Multiplier for locked-wheel stopping distance (reference temperature is 25°F).

The maintenance of steering capability under adverse roadway surface conditions is obviously an important matter. Its importance becomes even greater if the driving capability of the vehicle under such circumstances is increased while the maneuvering capability is not.

The Committee on Winter Driving Hazards has performed numerous tests of sustained cornering capability through the use of an ice circle (4). The circular course has a radius to the inner edge of the ice of 200 ft and a path width of 50 ft. A 12-ft lane is delineated on the ice surface by using rubber traffic cones; it has a known radius somewhere between 200 and 250 ft. The test vehicle is driven onto the delineated 12-ft width and the driver then accelerates until he is maintaining the highest speed possible around the course without continually slipping. His progress around the circle is timed for several revolutions, and his average speed is calculated. From the average speed and the known radius of the lane on which he is traveling, the average developed lateral coefficient of friction can be calculated. When such tests were performed on a passenger car that has new highway tread tires on both front and rear wheels, the average developed lateral coefficient was 0.071. It may be noted that this is close to the sliding coefficient of friction measured by locked-wheel stops on a similar course. When the test was repeated with new highway tread tires on the front wheels and new snow tread tires on the rear wheels, the average developed lateral coefficient was 0.072. With new highway tread tires on the front wheels and new studded snow tires on the rear wheels, the developed coefficient was 0.071. When new studded highway tires were used on both the front and rear wheels, the average developed lateral coefficient was 0.114.

From the foregoing it may be observed that increasing the driving traction on the rear wheels of a passenger car does not improve the sustained cornering capabilities of the vehicle. Observations made during the tests indicated that when no traction aid was applied to the drive wheels, the rear wheels of the vehicle were the fist to lose traction. Their performance limited the performance of the vehicle. When a traction aid was applied to the rear wheels only, the front wheels of the vehicle were the first to lose traction, and no improvement in sustained cornering capability was observed. When traction aids were applied to all four wheels of the vehicle, however, an appropriate improvement in sustained cornering capability was measured.

One circumstance in which the adverse effect on cornering resulting from the use of a traction aid on the rear wheels of the vehicle is common and is of some importance. Many modern automobiles have relatively high idle speeds, particularly shortly after start-up while the engine is still cold. Consider the case of such a vehicle having an automatic transmission and equipped with studded tires or tires with chains on the rear wheels. As it approaches a corner at which a turn is to be made or a driveway that is to be entered, the driver will apply brakes to decelerate to an appropriately low speed for making such a turn on an ice-covered surface. He will often find that, because of the effect of the high idle speed in continuing to drive the vehicle, the level of braking required to achieve deceleration will lock the front wheels. When he turns the steering wheel to undertake the steering maneuver, no cornering will occur and the vehicle will pass into or through the intersection or past the driveway. The solution to this problem appears to be to shift the automatic transmission into neutral as the vehicle approaches the point at which the turn is to be made, thus removing the driving force from the rear wheels (5).

For many years a number of ideas have circulated among drivers as to ways to improve vehicle performance under ice or snow conditions. Three of these are sufficiently widespread as to merit comment.

The first is the idea that adding weight to the rear of the vehicle will improve its performance. If a vehicle is to be driven through deep loose snow, where a certain amount of digging in is required, there may be limited merit to this procedure. The additional weight will provide some assistance in digging in, and the heavier weight on the drive wheels (against a given coefficient of friction) will permit the development of a greater force. On ice-covered surfaces, however, this procedure is not likely to be effective and may in some cases be detrimental. It has previously been demonstrated that more heavily loaded vehicles require longer distances in panic stops, and skid trailer tests have indicated that higher wheel loads result in lower measured coefficients of friction (6). Further, if the weight is added to the trunk of the vehicle aft of the rear axle, it will have the effect of reducing loading on the front wheels and, hence, reduce the maximum cornering force that can be developed. Carried to the extreme, this will adversely affect steering. Therefore, the procedure is not generally recommended.

The second is the idea that reducing tire pressure will improve vehicle performance under such adverse conditions. The Committee on Winter Driving Hazards has conducted extensive stopping-distance tests, skid trailer tests, traction tests, and limited cornering tests of a variety of highway tread, snow tread, and studded snow tread tires at inflation pressures of 12, 24, and 32 psi (7). In no case did reducing tire pressure below that recommended by the manufacturer result in improved performance. Although vehicle performance did not generally appear to be highly tire-pressure sensitive, some evidence was found that reductions in tire pressure to 12 psi resulted in performance degradation. Thus the reduction of tire pressure under ice and snow conditions is not recommended.

The third is the commonly held belief that radial tires will perform as well as snow tires when operating on snow-covered road conditions. The Committee on Winter Driving Hazards has made extensive tests of the pulling ability of bias-belted snow tires, bias-belted highway tires, and a variety of radial tires in snow. These tests indicated that the performance of a specific tire with respect to traction in snow is not associated with the construction of the tire but with the tire tread configuration.

It is true that many radial tires, not specifically designated as snow tires, will perform better in pulling traction in snow than will most nonradial highway tread tires. The superior ride characteristics of the radial tire permit the manufacturer to use as a conventional tread a somewhat more aggressive tread design than the public would be likely to accept as a general use tread on nonradial tires. To the extent that the tread design is more aggressive on the radial tire, the radial tire will perform better in snow.

Because of the widespread interest (and equally widespread misunderstanding) of this topic, it is appropriate to quote here one paragraph from the Committee on Winter Driving Hazards' report (1):

> The real thrust of these findings is that tire performance in traction on snow covered surfaces is not a function of tire construction--it is a function, primarily, of tread configuration. When a radial tire has a snow tread, it performs as a snow tire; when it has a tread approaching a snow tread, its performance approaches that of a snow tire; when it has a summer (highway) tread, its performance is that of a summer tire.

In summary, it may be stated that a driver operating an automobile over ice- or packed-snow-covered highways is operating under what is probably the most hostile and least-forgiving environment that he is likely to encounter. His primary concern must be to avoid breakaway between the vehicle tires and the surface over which it is traveling. Such breakaway can occur quickly as a result of excessive cornering. All such maneuvers should be avoided, and the best avoidance technique in general is to drastically reduce the speed of operation.

When breakaway does occur, as it almost inevitably will from time to time under such conditions, the driver will find that vastly greater distances are required to complete a desired maneuver or to recover control of the vehicle than is the case when operating over bare pavements. He should, therefore, greatly increase his following distance from the vehicle ahead of him--by a factor of 8 to 10 times that which he would maintain on a dry bare pavement surface. The heavier the vehicle that he is operating, the greater should be the following distance that he maintains.

Traction aids such as studded tires or tire chains can be helpful to the driver. He should, however, be thoroughly familiar with what kind of assistance and the magnitude of the assistance they provide. He should not count on more than they can deliver.

Finally, the driver should be continually mindful that, even with the best traction aids, the total traction available to him to propel his vehicle, stop his vehicle, and perform turning maneuvers is drastically less than that available to him when traveling over even a relatively poor quality rain-slick highway.

Earth, Sand, Gravel, and Mud

Concerning the influence of mud, sand, or gravel on the paved surface, it has long been understood that these materials can produce loss of control if significant maneuvers--stopping, accelerating, or cornering--are attempted. Loose sand or gravel on turns is a critical hazard to motorcyclists, perhaps constituting the most common cause of loss of control. It is of lesser significance to automobiles, but it is still of importance. Figure 2 shows loose gravel on a country road. Under certain circumstances this surface can contribute to a loss of

FIGURE 2 Loose gravel along the side of a country road.

control. In Figure 3 the result of an emergency steering input at high speed on the same road is shown. Mud can have much the same effect.

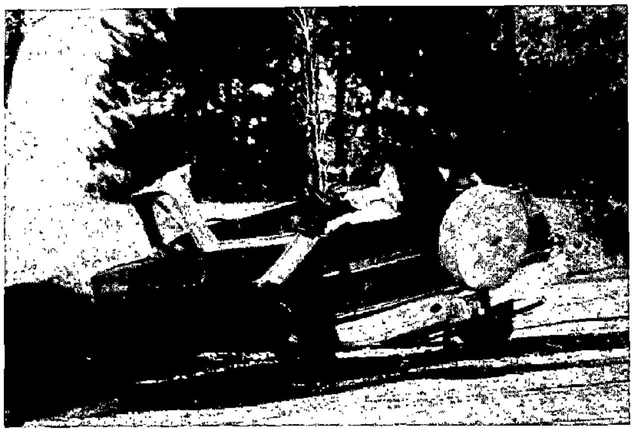

FIGURE 3 The result of an emergency steering maneuver at high speed (the Chevrolet Blazer was moving at a speed greater than 50 mph and in the center of the road when suddenly confronted by an oncoming vehicle).

In 1981 D.L. Ivey and R.A. Zimmer conducted a series of locked-wheel stopping-distance tests by using a 1976 Ford custom pickup (these data are from an unpublished experiment conducted on Project 2238 for the Texas State Department of Highways and Public Transportation, October 28, 1982). The road surface was a rounded gravel chip seal with a texture of approximately 0.04 in. This surface was coated with about 1 in. of east Texas silty clay and thoroughly wet. The results of the tests of stopping distance are shown in Figure 4. By observing the position of the test curve and comparing that position with the calculated curves of f = 0.3, 0.4, and 0.6, it can be seen that the average stopping coef-

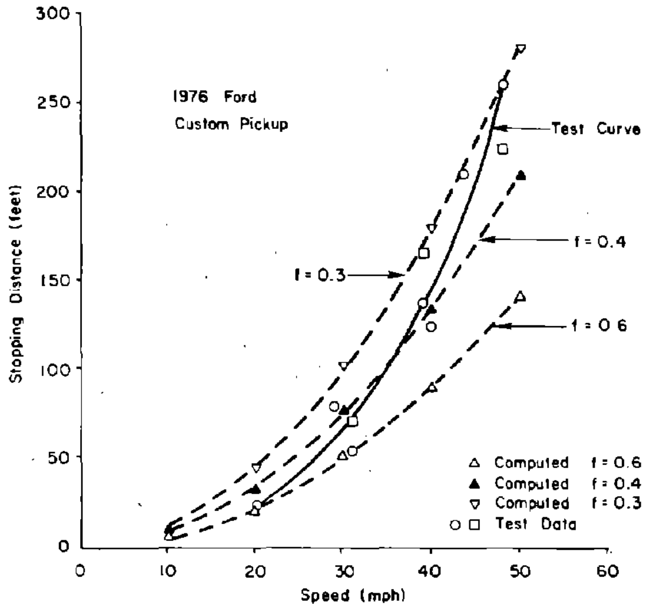

FIGURE 4 Stopping distance on wet clay-coated surface.

ficient decreases with speed, from 0.6 at 20 mph to 0.3 at 50 mph. Because of the relatively high texture of the paved surface, these coefficients may be high compared to what mud would normally allow. At speeds up to 50 mph, a nonprofessional test driver used abrupt steering maneuvers and made lane changes without losing control. In only one of the stopping-distance tests did the vehicle spin-out. The spin was approximately 90 degrees.

The data in Table 1 (8) was presented in a paper published in 1924 by Agg (8). Agg gives values of locked-wheel friction on gravel, natural soil, and sandy soil. The values vary from 0.26 to 0.34. Further work by Professor Agg (9) was presented in 1928 and is given in Table 2 (9).

TABLE 1 Values of Coefficient of Friction When Sliding Is Normal to Path of Vehicle *(8)*

Type of Surface	Condition of Surface	Size and Type of Tires	Weight on Rear Wheels	Total Starting Force in Pounds	Friction, f[a]
Pneumatic Tires					
Smooth concrete	Dry	33x4 Federal and Royal cord	1,870	600	0.387
Good asphalt	Dry	33x4 Federal and Royal cord	1,870	495	0.318
Fair wood block	Dry	33x4 Federal and Royal cord	1,870	380	0.245
Gravel	Spongy	33x4 Federal and Royal cord	1,870	405	0.261
Natural soil	Spongy	33x4 Federal and Royal cord	1,870	465	0.300
Smooth concrete	Dry	36x6 Goodrich DeLuxe cord	2,770	485	0.401
Good bitulithic	Dry	36x6 Goodrich DeLuxe cord	2,770	915	0.415
Wood block	Dry	36x6 Goodrich DeLuxe cord	2,770	950	0.431
Good gravel	Dry	36x6 Goodrich DeLuxe cord	2,770	760	0.344
Carpet coat	Dry	36x6 Goodrich DeLuxe cord	2,770	920	0.417
Loose sandy natural soil	Spongy	36x6 Goodrich DeLuxe cord	2,770	700	0.318
Solid Tires					
Smooth concrete	Dry	36x6 badly worn	2,560	650	0.324
Good bitulithic	Dry	36x6 badly worn	2,560	605	0.301
Fair wood block	Dry	36x6 badly worn	2,560	670	0.334
Natural soil (sandy)	Spongy	36x6 badly worn	2,560	540	0.269
Gravel	Dry	36x6 badly worn	2,560	600	0.299
Carpet coat	Dry	36x6 badly worn	2,560	700	0.348
Gravel (good)	Dry	36x6 dual tread	4,360	1,135	0.290
Carpet coat	Dry	36x6 dual tread	4,360	1,235	0.312
Natural soil, sandy	Spongy	36x6 dual tread	4,360	1,050	0.266
Good concrete	Dry	36x6 dual tread	4,360	1,285	0.325
Bitulithic (good)	Dry	36x6 dual tread	4,360	1,110	0.281
Fair wood block	Dry	36x6 dual tread	4,360	1,330	0.336

[a]f = (Total force producing sliding in pounds) ÷ (Weight of sliding wheels in pounds).

TABLE 2 Coefficient of Friction Between Tires and Road Surfaces When Sliding is in the Line of Travel *(9)*

Type and Condition of Road Surface	Size and Type of Tire	Tire Pressure (psi)	Road Dry		Road Wet	
			F[a]	f[b]	F[a]	f[b]
Gravel, feather-edge type with	A	30	0.69	0.66	0.60	0.55
some loose sand and pebbles	B	40	0.64	0.59	0.64	0.56
on surface; ruts slightly	B	50	0.66	0.62	0.64	0.58
when "wet"	B	60	0.61	0.58	0.64	0.59
Earth road, slightly sandy soil,	A	30	0.70	0.66	0.44	0.37
smooth and firm; ruts slightly	B	40	0.67	0.64	0.69	0.60
when "wet"	B	50	0.67	0.64	0.66	0.60
	B	60	0.68	0.66	0.58	0.52
Soft mud	A	30	–	–	0.34	0.29
Oiled earth 3 weeks old	A	30	0.72	0.69	–	–
	B	40	0.69	0.65	–	–
Packed cinders	B	50	0.67	0.60	–	–

Note: Measurements made by sliding the 4 wheels of chassis.
[a]F = (Force required to start the tires sliding) ÷ (Normal pressure between tire and road).
[b]f = (Force required for uniform sliding) ÷ (Normal pressure between tire and road).

R.A. Moyer extended Agg's work through the 1930s; and he is still active, having recently presented a history of skid resistance research to ASTM and aided in this work by publishing many excellent references. In a definitive work by Moyer in 1934 (10), the following is found.

Mud on Pavements

> Tests on a mud-covered pavement clearly indicate how slippery such surfaces can be, the coefficients ranging from 0.2 to 0.3. These coefficients are only slightly higher than those obtained on ice, which is an indication that muddy pavements may be considered practically as hazardous as ice. The placing of gravel, shale, cinders, or crushed rock on the shoulders and at the approaches to all pavements would not only correct a dangerous skidding condition, but would provide greater road widths for use in an emergency.

Tests on Dry Surfaces

> The curves...show that the coefficients of friction for dry surfaces are 0.3 to 0.5 higher than for the same surface when wet, except in the case of cinders and untreated gravel, which were about the same, wet or dry. As with the wet surfaces, the coefficients for a number of dry surfaces decreased with an increase in speed, although the decrease was not as marked on the dry surfaces as when the same surfaces were wet. An increase in the side skid coefficient with an increase in speed was observed for the gravel, brick and asphalt plank surfaces.

It should be understood that simply the classification mud will not suffice to estimate available friction. Although it has not been experimentally verified, many things influence the available friction on a muddy paved surface. The most obvious are (a) the mineral constituents of the soil, (b) the degree of wetness and compaction, and (c) the texture of the underlying paved surface. One thing almost all have in common is that the available friction is reduced, and thus the potential for accidents by imprudent drivers is increased.

Diesel Fuel

A relatively uncommon but extremely dangerous road surface contaminant is diesel fuel. This section relates specifically to this product, although many types of petrochemicals are at times deposited in small amounts on highway surfaces.

Even small amounts of diesel fuel on a wet surface can cause a precipitous loss of available friction. Based on the extrapolation of British pendulum numbers to account for speed sensitivity, B.M. Gallaway developed Figure 5 (note that these data are from unpublished test series on wet road surfaces contaminated by diesel fuel; the research was performed by Consulting and Research Services in June 1983). Four different asphalt concrete (AC) pavements were included in the testing. These are designated G1, G2, shell mix, and worn pavement (see Table 3). Available friction may be reduced from 48 to 92 percent when diesel fuel is placed on a wet pavement. In the case of the worn pavement, the resulting friction is on the same order as wet ice.

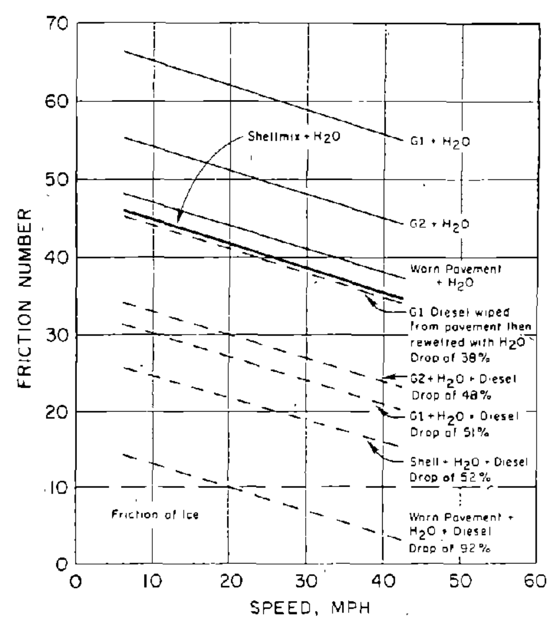

FIGURE 5 Influences of diesel fuel on available friction of wet pavements.

TABLE 3 Description of Pavement Surfaces

Designation	Type Pavement	Coarse Aggregate Type	Other Comments
G1	Hot mix ACP	Limestone	High macrotexture, but surface fairly well polished
G2	Hot mix ACP	Limestone	Medium macrotexture, high (unpolished) microtexture
Worn pavement	Hot mix, cold laid ACP	Siliceous rounded gravel	Flushing apparent, low macrotexture and microtexture
Shell mix	Hot mix ACP	Shell	Medium macrotexture

FIGURE 6 Eastbound lanes of the Calcasieu River Bridge over Lake Charles.

On the Calcasieu River Bridge over Lake Charles (Figure 6), a 26 car and truck accident took place on August 27, 1981 (11), when 75 gal of diesel fuel spilled from a ruptured tractor-trailer fuel tank. The spill occurred on the downhill eastbound side of the bridge, thus maximizing the need for friction by oncoming vehicles. Statements of the drivers involved in the accident verify the extreme slipperiness of the road surface in this condition. Although spills of this magnitude are rare, this event emphasizes the extremely hazardous nature of pavement so contaminated.

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CHAPTER 8 Small and Large Vehicles

Lindsay I. Griffin III and Thomas D. Gillespie

Special Considerations for Small Vehicles

An increased sensitivity of the small automobile to road surface discontinuities is indicated from accident data and increased probability of injury to the occupants of such vehicles. A recent study by Griffin (1) indicates that lighter-weight cars may be more likely to be involved in curb accidents than are heavier cars. In a study on tire defects, Campbell (2) presents data that suggest that small cars may be disadvantaged by roadway discontinuities and disturbances. In his article, Campbell demonstrates that accident-involved subcompact cars are far more apt to be cited for tire defects than are accident-involved large cars. Furthermore, this phenomenon is upheld when controlling simultaneously for vehicle age and driver age. Whether this phenomenon results from higher rates of rotation for smaller tires or from greater abuse suffered by smaller tires when striking ruts, potholes, edge drops, foreign objects, and so forth remains to be seen. Simply concluding that small vehicles are more sensitive to all surface problems does not appear to be warranted. In Chapters 3 and 4 (3,4) it was demonstrated by tests that a small vehicle could handle pothole traverses less effectively than a large car, but that it was no more sensitive to pavement edges than some larger vehicles.

Steward and Carroll (5) have noted that crash involvement rates for smaller cars are greater than for larger cars. Why this disparity in rates exists is not commented on. Perhaps smaller cars are driven by younger drivers, at higher speeds, or in different circumstances. Or perhaps roadway disturbances (e.g., inadequate friction) pose more severe problems for smaller cars than they do for larger cars.

A recent analysis by L.I. Griffin (unpublished data) suggests that smaller, lighter-weight cars may be more susceptible to skidding accidents than larger cars (see Figure 1). In this analysis single-vehicle accidents involving passenger cars of known curb weight were coded 1 if they resulted from skidding and 0 otherwise. Logistic regression procedures were then applied to estimate the influence of curb weight on the probability of an accident being classified as a skidding accident. A logistic regression equation of the following form was built:

$$Y = \exp(a + bX)/[1 + \exp(a + bX)] \qquad (1)$$

where

- Y = probability of an accident being coded as a skidding accident,
- X = vehicle curb weight, and
- a,b = regression coefficients.

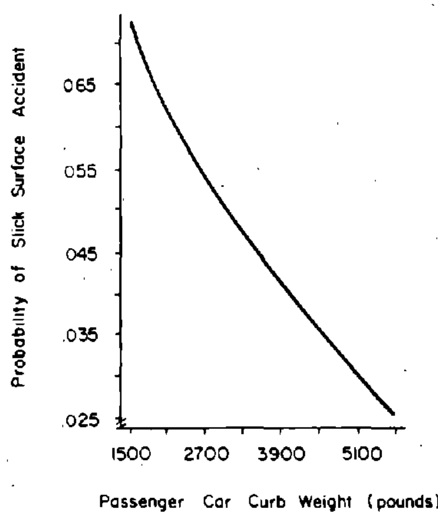

FIGURE 1 Probability of involvement in slick surface accidents as a function of passenger car weight.

The maximum likelihood estimates of a and b are $a = 2.17760701$ and $b = 0.00024691$. A chi-square test was carried out to determine if the two variables (X and Y) are independent. The resulting chi-square was 59.34 ($p < 0.0001$), which indicates they are not.

Whether the relationship depicted in Figure 1 results from the simple physical interaction of road surface characteristics and passenger car curb weight or other spurious factors that vary with vehicle weight (e.g., driver age, speed) will require further research. The fact that vehicle wheel base and track width are smaller with the lighter vehicles implies reduced directional stability, which provides a relatively direct explanation of the apparent susceptibility of these smaller vehicles to slick surface accidents.

Special Considerations for Large Vehicles

Thus far the geometry of the roadway surface has been discussed largely from the perspective of how it influences safety of passenger cars. In this section the attention turns to the larger vehicles used for commercial transportation. Commercial vehicles encompass the spectrum of vehicles used to transport goods, ranging from the two-axle medium truck with a gross vehicle weight of 15,000 lb to the heavy-class articulated tractor-trailer combinations that may have from 3 to 11 axles and may operate at gross combination weights of 72,000 to more than 150,000 lb. Likewise, the commercial vehicle class includes buses used for transporting passengers that fall in the midrange of the sizes just described. In total, commercial vehicles represent about 20 percent of the vehicles on the highway. Of these, approximately one-half are the common tractor-semitrailers, which are the primary focus in the following discussion.

Accidents with commercial vehicles risk injury or death not only to their own occupants but especially to other motorists. Because of their weight disparity with other vehicles on the road, occupants of other vehicles are more frequently killed in collisions with combination vehicles. The statistics are illustrated in Figure 2, which shows the distribution of fatalities in different types of vehicles, taken from the 1980 Fatal Accident Reporting System (FARS) data (6). In accidents between combination vehicles and passenger cars, 1,775 occupants of passenger cars were killed in contrast to 53 occupants of combination vehicles.

The same study (6) also provides some insight into the significance of roadway surface condition as a first factor contributing to truck-car accidents. Figure 3 shows that, among the 20 possible first contributing factors coded in a 1979 Pennsylvania study, the roadway condition was the sixth most important.

Because of their size and design, large commercial vehicles have characteristics that are uniquely different from passenger cars, which affects their sensitivity to roadway discontinuities. Those differences are seen in the roadway characteristics relating to the response to roughness discontinuities in the roadway and to tire-road friction coupling.

Discontinuities in the surface of a road that would fall in the classes of generalized roughness, potholes, edge drops, or other special features will affect commercial vehicles differently than passenger cars. Because of the larger tires used on these vehicles, the abrupt features are normally not as significant as an input to large vehicles. That is, a truck tire running through a pothole or over a curb edge, because of its size, is able to negotiate the feature with less disturbance to the vehicle. Such discontinuities impose a vertical and a longitudinal force on the wheel, the relative magnitude of which is inversely proportional to tire size. This relationship holds because trucks have larger tires that tend to smooth out the abrupt discontinuities, and they have more deflection distance available within the tire to absorb the disturbance.

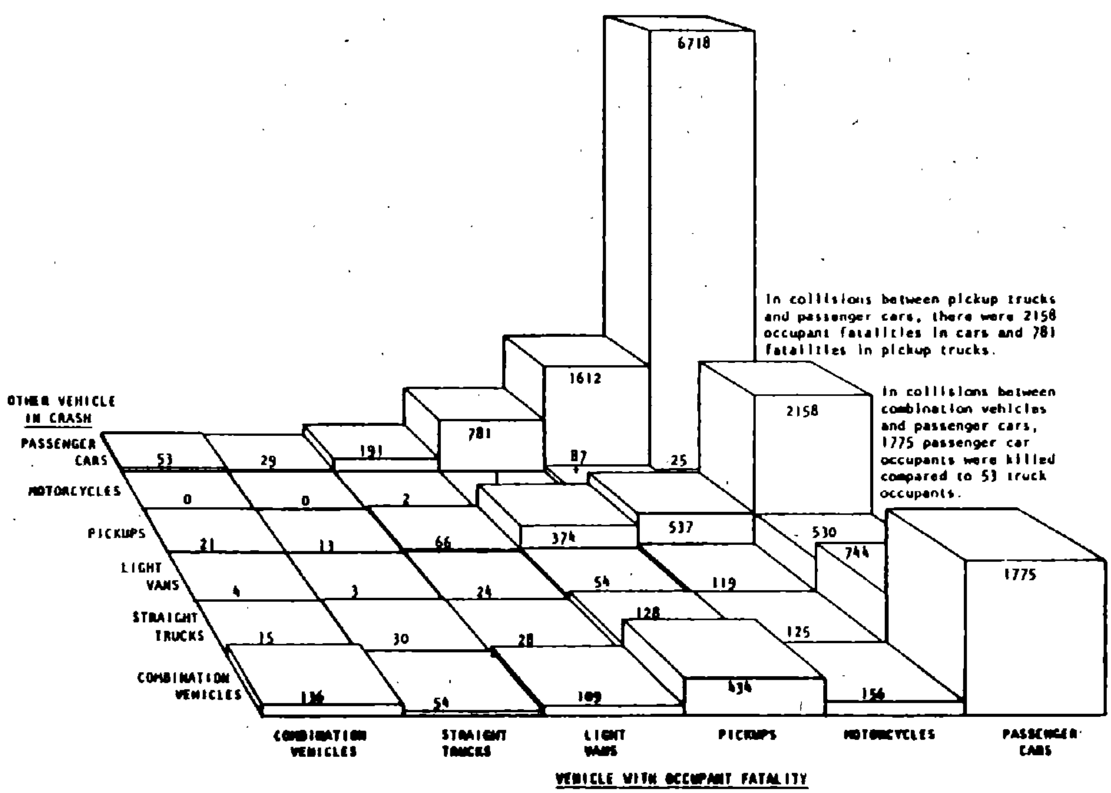

FIGURE 2 Occupant fatality distribution by mix of vehicles, U.S. two-vehicle fatal crashes in 1980 (N = 17,137).

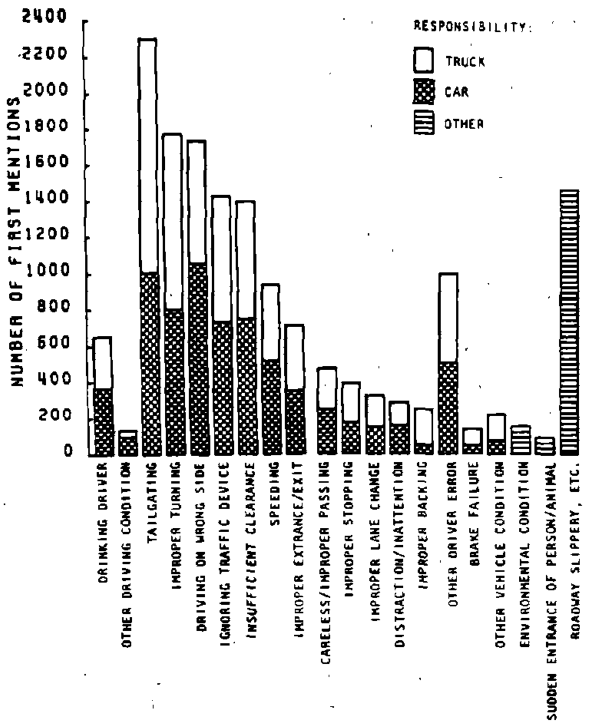

FIGURE 3 Responsible first contributing factors in 1979 two-vehicle truck-car crashes in Pennsylvania.

Counterbalancing the advantage gained from the larger size of truck tires is the reduced isolation provided by their typical suspension systems, stiffer springs, and higher tire pressures. In order to maintain appropriate vehicle positions over a broad range of load conditions, the more common suspension types must have a high effective stiffness. As a consequence, those disturbances imposed through the tire are more directly transmitted to the vehicle chassis.

No definitive research has been done to quantify the sensitivity of large vehicles to the more abrupt features in the nature of potholes, curbs, or pavement edge drops. From the knowledge of truck dynamic properties, it may be expected that certain types of these road features can create a greater vibration disturbance to trucks than to cars. In addition, there exists the concern that such road features may produce a steering disturbance, with potentially greater consequence to a truck. Yet until such research is performed, no conclusions can be proffered.

In the broader area of generalized roughness in roads, there has been some recent research to determine its influence on safety (7). It may be concluded from that study that truck vibration response to road roughness is qualitatively similar to passenger cars, albeit at a much higher level. It may be inferred that, on average, roads that appear rougher to cars are also rougher to trucks. Hence the effort to maintain roads to acceptable levels of roughness for passenger car use will, at the same time, keep them generally suitable for trucks. Although the vibration levels induced on trucks by road roughness are much higher than on passenger cars, that same study concludes from a polling of experts that there is no direct link to safety of operations.

Perhaps the one area of possible influence that has not been well addressed in the literature is the significance of special wavelengths of road roughness to which trucks may be sensitive. It is known among experienced truck drivers that certain long wave road undulations, as typified by pavement settlements in bridge approach areas, may be peculiarly difficult to negotiate with commercial vehicles, particularly tractor-semitrailers. These features tune to the low-frequency rigid-body bounce and pitch modes of these vehicles. Because the drivers are located near the extremities of the vehicle (far from the center of gravity), large displacement vertical and fore-aft motions can be imposed on the driver, thus complicating the task of maintaining control when negotiating these road features. There is anecdotal evidence that truck drivers have experienced control problems reflecting on safety due to these effects, but there has been no known effort to compile statistics quantifying the magnitude of this particular problem. Unfortunately, available accident data are not specific enough in their recorded detail to provide that answer.

In summary, it must be concluded that the knowledge is deficient to state with confidence which road features constitute peculiar safety problems for large vehicles. Relying on the general knowledge of such vehicles, however, points to the need to better understand certain long wavelength roughness qualities in roads as potentially unique problems for such vehicles.

Commercial vehicles achieve their greater load-carrying capacity not only by the use of more axles but also by the use of larger tires operated at higher inflation pressures. The higher road-tire contact stresses thus obtained are also cause for the use of tread rubber compounds that differ from those commonly used on passenger-car tires. Thus it is not surprising to find that truck tires exhibit traction qualities distinctively different from passenger-car tires. Quantitatively, truck tires exhibit lower peak tractive force coefficients of friction on a given surface (8), the sliding coefficient of friction is proportionately even lower (8,9), and truck tire traction qualities are more linear with load (10).

The traction differences of truck tires, either on dry or wet roads, do not appear to have a major safety significance because the vehicles' accident-avoidance capabilities are not as uniquely traction limited as with passenger cars. Intuitively, it can be hypothesized that commercial vehicle safety would be linked to emergency braking capability and to limited cornering capability.

Studies of the safety benefits accrued from higher performance airbrake systems (11), however, fail to demonstrate any benefit from improved stopping-distance performance. Thus it would be inferred that the nominal traction limits of current truck tires on the road are not significant to safety in braking situations. Although this conclusion has broad implications, it can be rationalized for some situations, but not others. On dry pavements truck braking capability is normally more limited by vehicle design than by road friction characteristics. On lightly wetted roads truck tire traction is not severely disparate from that of passenger-car tires, and in the case of heavy water accumulations, the higher contact pressures under truck tires undoubtedly result in greater resistance to hydroplaning, except possibly in the case of lightly loaded tires.

Ice- and snow-contaminated conditions are most critical for commercial vehicles (12). The more critical nature arises from several key differences: articulated vehicles have unique modes of instability (e.g., capability to jackknife), accidents are more severe because of greater size and mass, and

TABLE 1 Number of Tractor-Trailer and Doubles Accidents from 1980 FARS Data

Vehicle Weight (lbs)	Accident Type	Road Condition Dry	Wet	Snow	Ice
10,000–30,000	All Accidents	483	101	22	20
	Jackknife	49	24	11	5
	(Percent)	(10.1%)		(28.0%)	
30,000–50,000	All Accidents	448	84	16	17
	Jackknife	30	14	1	3
	(Percent)	(6.7%)		(15.4%)	
50,000–70,000	All Accidents	575	104	16	29
	Jackknife	42	15	7	4
	(Percent)	(7.3%)		(17.4%)	
70,000–90,000	All Accidents	756	100	17	24
	Jackknife	68	13	3	6
	(Percent)	(9.0%)		(15.6%)	

these vehicles are more prone to rollover, even in the absence of a collision.

The higher tire contact pressures that resist hydroplaning on wet roads can be a detriment on ice- or snow-covered roads. Except at extremely low temperatures, the low friction coupling on ice-covered roads is dominated by the water film developed on the surface caused by frictional heating (13) and the contact pressure of the tire. Inasmuch as truck tires have higher loads and contact pressures, the low friction level is likely to prevail over a much wider temperature range than occurs with passenger-car tires. The combination of all these factors is then cause for greater concern for the safe operation of large commercial vehicles on snow- and ice-covered roads.

The cornering performance limits of commercial vehicles are established by two predominant modes--rollover and yaw instability (13). Rollover, in and of itself, is not an accident-causation factor that is aggravated by deficient road surface conditions. The rollover limit has a first-order relationship to the ratio of center-of-gravity height to track width, thus making it specific to the vehicle. Road friction is only significant in the sense that its nominal level will determine whether rollover is possible while the vehicle remains on the road. That is, the rollover limits for many commercial vehicles are low enough that rollover (rather than simple spin-out) is possible with loss of control on dry roads, although not as certainly on wet roads. At the same time the risks of loss of control are also greater on wet roads. Of course, once a combination vehicle has left the road, the probability of rollover is greatly increased by roadside cross slopes and soft soil conditions.

The second limit mode--yaw instability--is a technical term describing the onset of jackknife with articulated vehicles or spin-out with straight trucks (13). By the nature of the way in which the load is carried, and the way in which the roll resistance is shared among axles on commercial vehicles, their turning performance is most often limited by loss of cornering force on the rear axles of a truck or tractor. When this occurs, spin-out follows, with a subsequent risk of rollover. The loss of cornering force is, in part, a function of the road surface and its friction level. In pure cornering maneuvers, the threshold of instability occurs at rather moderate slip conditions (3 to 5 degrees of slip angle), where the cornering force properties are much more dependent on the stiffness of the tire carcass than on the tire-road coefficient of friction. However, when braking is also combined with cornering, brake slip at the rear wheels will contribute to loss of cornering force and subsequent jackknife. Consequently, the potential for this type of accident is greatest when the vehicle is unloaded or when the tire-road coefficient of friction is low. The effect shows up in the accident statistics such as the 1980 FARS data for tractor-trailers and doubles (see Table 1). Taking the 10,000- to 30,000-lb weight as indicative of unloaded vehicles, and the 50,000- to 70,000-lb weight as typical of loaded vehicles, the statistics can be summarized as follows:

1. On dry pavements jackknife is involved in about 7 percent of all fatal accidents of loaded combination vehicles and about 10 percent of those for unloaded vehicles, and
2. On wet, snowy, or icy roads the jackknife involvement increases to nearly 17 percent for loaded vehicles and 28 percent for unloaded vehicles.

Thus from the standpoint of tire-road friction

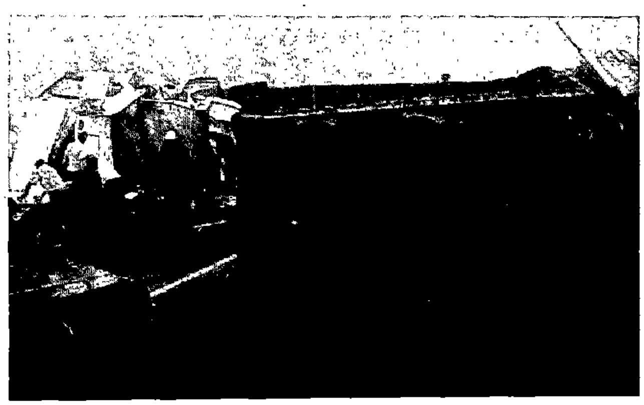

FIGURE 4 Serious truck accident under wet weather conditions.

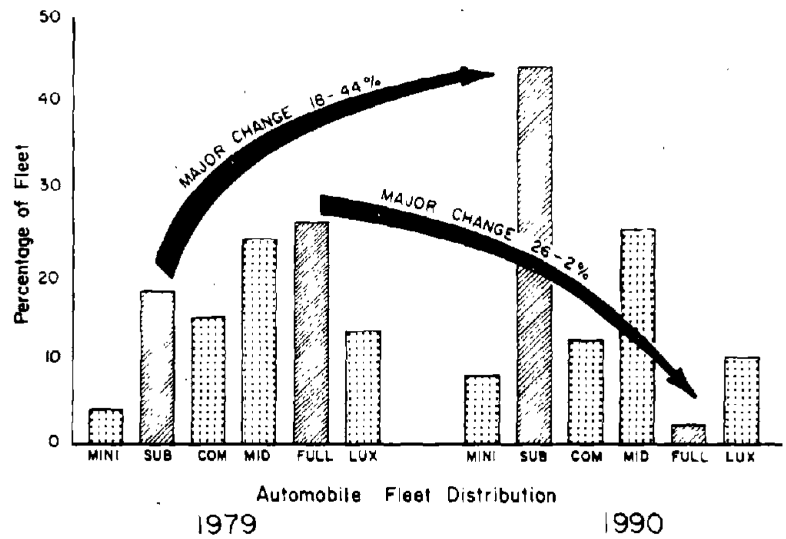

FIGURE 5 Shift in automobile size distribution.

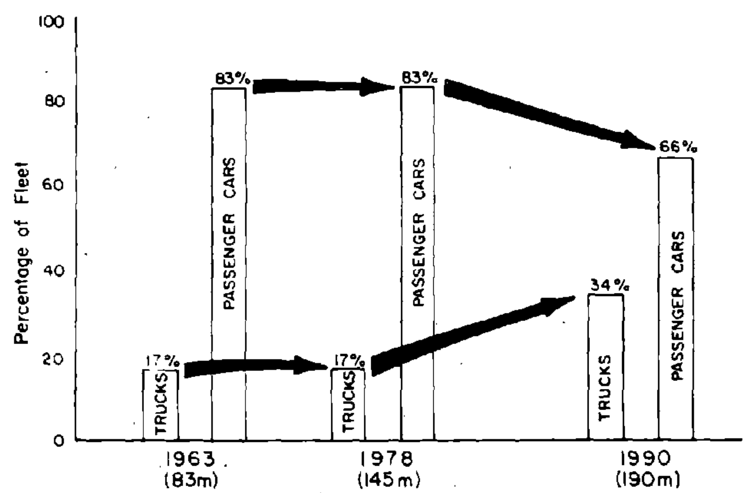

FIGURE 6 Shift in population distribution between stucks and passenger cars.

coupling, it is concluded that the safety performance of large commercial vehicles is uniquely critical on roads contaminated with water, ice, or snow. The threat to large vehicles under these conditions arises from the potential for loss of control, thus leading to more severe accidents; even at low speeds, jackknife or rollover accidents, like that shown in Figure 4, are possible.

The highway vehicle spectrum is changing rapidly. Figure 5, presented by C.V. Wootan, shows an estimate of shifts the automobile population will undergo by the year 1990 (note that these data are from an unpublished presentation, The Changing Vehicle Mix and Its Implications, given to the Texas Institute of Traffic Engineers in El Paso, February 1980). The small end of the spectrum, represented primarily by subcompacts, shows these vehicles becoming the dominant passenger automobile.

The way in which the large end of the spectrum is shifting is shown in Figure 6. Wootan suggests that trucks will make up 34 percent of the vehicle population by 1990. This segment of the vehicle population, including formidable 18-wheelers, double-bottoms, and even triple-bottoms, is increasing in number precipitously, and increasing in size and weight as fast as the technical, economic, and political climates will allow.

With these major changes occurring, which influence both the creation of road surface discontinuities and the sensitivity of vehicles to them, far more effort may be warranted to determine the interactions between vehicle size and the roadway surface problems that influence traffic accidents.

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CHAPTER 9 Conclusions

The analysis of 15,968 single-vehicle accidents in North Carolina conducted in 1974 yielded the first statistical indication of the influence of road surface discontinuities on highway safety. Narratives containing 1 of 19 key words (e.g., dip, rocks, rut, edge) were examined and reviewed to determine if an accident resulted from, or was aggravated by, a roadway discontinuity. Some 566 (3.5 percent) of the 15,968 accidents were associated with roadway irregularities. Other reviews of accident data from three sources--California accident data (police reports), collision performance and injury report (CPIR) data provided by the Highway Safety Research Institute of the University of Michigan, and Indiana accident data (levels II and III) provided by Indiana University--indicated that the roadway disturbances shoulder drop off and loose material on roadway had a significant influence on safety. Other irregularities such as potholes, rough roads, and dips have been identified as potential problems.

The main findings of the Task Group resulting from this study concerning specific types of roadway surface discontinuities follow.

TIRE PAVEMENT FRICTION (CHAPTERS 2 AND 5)

- The influence of surface friction has been a favorite subject of researchers for many years. To assume that traffic accidents, or a given subset of traffic accidents (e.g., accidents that result from inadequate surface friction), can be accurately predicted on the basis of one condition (such as skid number) is wishful thinking. It should be recognized that the frictional properties of a road surface are not inherently adequate or inadequate, but can only be so classified in terms of specific vehicle maneuvers--stopping, turning, or accelerating (i.e., vehicle demand for friction). This fact has been recognized directly or indirectly in a number of studies.
- Variations in friction coefficients within and between wheel paths may produce difficulties in controlling a vehicle when brakes are applied. This phenomenon was first described theoretically in 1959. It was concluded that a difference in the friction coefficients of the wheel paths could be potentially hazardous, even though the average surface friction is relatively high. Severe vehicle response may occur when a driver releases his brakes after his vehicle has begun to spin. The rotating vehicle may run off the pavement or into other vehicles.
- Variations in the friction properties of pavement surfaces in the direction of travel occur frequently. Whether drivers judge changes in friction properties correctly, or even realize the existence of such changes, is debatable, as is whether they adjust their driving pattern to perceived changes. Because all changes are not perceived, and others are likely to be judged incorrectly or ignored, they can constitute a potential hazard. From the viewpoint of safety, there is little doubt that longitudinal variations in pavement properties should be avoided. If this cannot be done, these variations should be minimized within the boundaries of appropriate maintenance priorities.
- Marking materials generally lower the skid resistance of a pavement. When applied over large sections, skid stopping distances are increased. Differential friction caused by the application of marking materials may also give rise to hazardous situations, such as excessive vehicle yaw during locked-wheel skids, loss of control during motorcycle or bicycle turning and braking maneuvers, and slipping and falling by pedestrians on crossings. Single and double delineation stripes do not appear to be a problem.
- Single-vehicle loss of control resulting from the inability of some drivers to deal with a lower friction shoulder surface causes some accidents. After running off the paved surface, if a driver reacts quickly with too much steering input, a large steering force may result when the offside front wheel strikes the paved surface. Collision or rollover may result. The high lateral acceleration produced by this maneuver further complicates recovery by an unbelted driver, who may be thrown out of position to properly control the vehicle.

ROUGHNESS, HOLES, AND BUMPS (CHAPTERS 3 AND 8)

- It is apparent that a hole must be relatively large to constitute a significant safety influence. At common highway speeds a hole must be in excess of 60 in. long and 3 in. deep to constitute a threat to the smallest automobile. On urban streets, with traffic speeds as low as 20 mph, holes must be 30 in. long and 3 in. deep to have the potential of damaging tires and rims. Damage to tires and rims, with the potential for an air-out, is the significant safety-related influence of holes identified in vehicle handling studies. Problems can arise if a driver reacts to the hole inappropriately. For example, it is counterproductive to react with braking or extreme cornering to a hole in a vehicle's path.

- A prudent driver recognizes the problem of a rough road and adjusts his speed to meet the conditions encountered. Consistent roughness is not necessarily a negative influence on safety. Violation of driver expectancy by precipitously going from a smooth surface condition to extremely rough conditions may constitute a relatively unsafe condition.
- Under certain conditions curbs may have a negative influence on safety. Recommendations have been made regarding barrier height as a function of barrier setback from the curb. Highway Research Board Special Report 81, published in 1964, alluded to possible problems if high curbs are used in front of guardrails. A subsequent study (NCHRP Report 150, 1974) states: "It has been found that curbs offer no safety benefit on high-speed highways from the standpoint of vehicle behavior following impact." The AASHTO Barrier Guide of 1977 recommended that a curb should not be used as a redirective device, and if used with a barrier the face of the curb should be no closer to the traveled way than the face of the barrier.
- Smaller cars are more likely to be involved in curb accidents than are larger cars. Handling and stability problems associated with car-curb involvements are probably inversely related to car size. It is strongly suggested in the literature that curb impacts by errant motorists on high-speed facilities may result in loss of vehicle control and potential overturning. On high-speed facilities, delineation drainage and traffic control should be achieved by other means.

WATER ACCUMULATIONS (CHAPTER 6)

- Hydroplaning is a low-probability event, primarily because high intensity rainfalls necessary to flood a pavement are low-probability events. When hydroplaning does occur, it can result in loss of steering and directional instability. Criteria for surface design to further reduce the probability of hydroplaning have been developed and are cited.
- Splash and spray can affect driver visibility and thus safety. Low places in the pavement surface that hold water or flat spots that drain poorly contribute to the splash and spray problem. Increasing surface texture or providing porous self-draining pavements (in favorable climates) can contribute to better visibility; but maintaining these surfaces may be difficult. Some fender systems for trucks have been devised to reduce splash and spray, but these can be costly an can create operational problems. Side skirts and spray-suppressant mud flaps are steps in the right direction. However, until a major breakthrough occurs, the driver must use extreme caution when environmental conditions result in visibility reduction.

SURFACE CONTAMINANTS (CHAPTER 7)

- The primary influence of ice and snow is loss of traction. Although many roadway surface contaminants result in reduced tire-pavement friction, the magnitude of the loss experienced when traveling on packed snow or ice exceeds that of most other contaminants. Most dry pavements will exhibit friction coefficients in excess of 0.7. The same pavements when wet may exhibit friction values as low as 0.25 and still provide adequate surfaces for normal traffic operations where traction demands are modest. When the surface is covered with ice and the temperature is near the freezing point, the available friction may be as low as 0.05. The capability of the vehicle to move, corner, or stop is greatly reduced. A driver operating an automobile on highways covered with ice or packed snow is operating under a most hostile and least-forgiving environment. His primary concern must be to avoid breakaway between the vehicle tires and the surface over which he is traveling. Such breakaway can occur quickly as a result of modest braking or cornering, which should be avoided. Prudent drivers familiar with ice and snow conditions reduce speed radically.
- Mud, sand, or gravel on the paved surface can produce loss of control if significant maneuvers involving stopping, accelerating, or cornering are attempted. Loose sand or gravel on turns is a critical hazard to motorcyclists, perhaps constituting the most common cause of control loss. It is of lesser significance to automobiles, but it is still of importance.

PAVEMENT EDGES (CHAPTER 4)

- Studies consistently reveal a significant influence of longitudinal pavement edges on vehicle safety. Loss of vehicle control may occur at speeds greater than 30 mph under certain circumstances, where inattentive or inexperienced drivers return to the traffic lane by oversteering. This safety problem is minimized where the pavement edge drop does not exceed 3 in. in height or the edge is rounded or sloped. Pavement edges 5 in. or more in height can interfere with the underneath clearance and thus create safety problems for small automobiles.

SMALL AND LARGE VEHICLES (CHAPTER 8)

- Vulnerability of small automobiles to road surface discontinuities is indicated by accident data. The probability of injury during a collision is also increased for small vehicles. Crash involvement rates for smaller cars are greater than for larger cars. Smaller cars may be driven by younger drivers, at higher speeds, or in different circumstances, or roadway disturbances may pose more severe problems for smaller cars than for larger cars.
- Large commercial vehicles, because of their size and design, may be more sensitive than passenger cars to some surface discontinuities. Those differences are seen in roughness re-

sponse and sensitivity to low tire-road surface friction.

- No definitive research has been done to quantify the sensitivity of large vehicles to more abrupt features such as potholes, curbs, or pavement edges. From the knowledge of truck dynamic properties, it may be expected that certain of these road features can create a greater vibration disturbance to trucks than to cars.

- Ice and snow on road surfaces are more critical for certain commercial vehicles. The critical nature arises from several differences between commercial vehicles and passenger cars: articulated vehicles have unique modes of instability (e.g., capability to jackknife), accidents are more severe because of greater size and mass, and these vehicles are more prone to rollover, even in the absence of a collision.

SUMMARY

Most drivers are capable of adapting to adverse circumstances. Because of this capability, many potentially dangerous surface problems never cause a serious accident. The danger, however, is sometimes critical with respect to the unwary, the distracted, or the imprudent driver. Engineers have traditionally constructed and maintained reasonably safe highways, and most drivers expect satisfactory surface conditions. Road conditions that were acceptable when the U.S. highway transportation system was developing are not acceptable to the public today because of this driver expectancy. Complicating the problem is the fact that responsible government entities do not have the funds available to maintain all highways in as-constructed condition. The need to use these limited maintenance funds on a priority basis is critical. There is a need for highway engineers to assess their maintenance policies by using the best available information. The Task Group trusts that this report provides much of the required information.

APPENDIX

Biographical Data

DON L. IVEY, Task Group Leader, is Associate Director of the Texas Transportation Institute and a Professor of Civil Engineering at Texas A&M University. Professor Ivey received his Ph.D. in Civil Engineering from Texas A&M University in 1964. He was formerly the Head of the Safety Division, Collision Dynamics Laboratory, and Structural Research Laboratory, all of the Texas Transportation Institute. Professor Ivey was chairman of Transportation Research Board Committee A2B07 (Committee on Surface Properties-Vehicle Interactions) from 1975 through 1981, and he is currently a member of ASTM Committee E17 on Traveled Surface Characteristics. He is currently active in this and other research fields related to highway safety.

JOHN C. BURNS is Vice President of Testing Engineers-San Diego. He is a graduate of the University of Arizona, receiving his BS degree in Geological Engineering in 1969, and is a registered civil engineer in California, Arizona, and Florida. With 19 years experience, he has authored more than 25 papers in the field of pavement evaluation and has received several honors, including Young Engineer of the Year, Arizona Professional Society of Engineers, and the K.B. Woods Award, Transportation Research Board, National Research Council, 1977. Mr. Burns is listed in Who's Who in the West, Who's Who in Technology Today, and Men of Achievement, International.

THOMAS D. GILLESPIE is a Research Scientist at the Transportation Research Institute, University of Michigan, Ann Arbor, Michigan. In 1970 Dr. Gillespie received his Ph.D. in Mechanical Engineering from Pennsylvania State University. In addition to basic research into the dynamics of vehicle ride, braking, and handling, he teaches machine design and vehicle dynamics. Among Dr. Gillespie's many consulting activities, he is aiding the World Bank in the development of road roughness measurement standards for use worldwide.

LINDSAY I. GRIFFIN III is Head of the Accident Analysis Division, Texas Transportation Institute, Texas A&M University. Dr. Griffin has spent the past 8 years developing one of the nation's premiere accident data bases, and he has conducted numerous unique statistical studies using that data base. He worked for 3 years with Dr. B.J. Campbell at the Highway Safety Research Center in North Carolina. Dr. Griffin published the first statistical study of road surface problems using police accident data in 1975. He is currently on a 1-year assignment with the Transportation Research Board, National Research Council. Dr. Griffin graduated from the University of North Carolina, Chapel Hill, with a Ph.D. in Experimental Psychology in 1975.

GORDON F. HAYHOE is an Assistant Professor of Mechanical Engineering at the Pennsylvania State University and is a Research Associate at the Pennsylvania Transportation Institute. Dr. Hayhoe received his Ph.D. in Mechanical Engineering from the Cranfield Institute of Technology in England in 1973. His major field of professional activity is the measurement of pavement surface properties, with special reference to skid resistance on wet and icy surfaces and the measurement of road roughness. Dr. Hayhoe also has experience in the fields of vehicle handling behavior and vehicle-driver interaction.

WALTER A. JOHNSON is a Principal Specialist at Systems Technology, Inc., Hawthorne, California. Mr. Johnson received his MA in Aerodynamic Engineering from the California Institute of Technology in 1960. Since then he has worked on a variety of vehicle dynamics problems. These problems have been primarily associated with vehicle control, handling, and safety. Mr. Johnson's 1976 report with Klein and Szostak, "The Influence of Roadway Disturbance on Vehicle Handling," produced the definitive theoretical explanation of the "pavement edge-vehicle control" phenomenon. He is currently conducting a major study of heavy vehicle splash-spray retarding devices for NHTSA, U.S. Department of Transportation.

WOLFGANG E. MEYER is Professor Emeritus of Mechanical Engineering at Pennsylvania State University. He was formerly the Director of the Automotive Research Program of the Pennsylvania Transportation Institute at Pennsylvania State University. He was engaged in research in, among other things, the field of tire-pavement friction. Professor Meyer has been chairman of TRB Committee A2B05 (now A2B07) and ASTM Committee E17 on Traveled Surface Characteristics. He continues to be active in these committees as well as in research and consulting work in the field of vehicle-pavement interaction and other related fields of study. Professor Meyer received his degree in Mechanical Engineering in 1935 from the Technical University of Hannover, Germany.

JOHN M. MOUNCE is Associated Research Engineer and Manager of the Urban Mobility Program at the Texas Transportation Institute, Texas A&M University. In 1980 he received his Ph.D. in Civil Engineering from Texas A&M University. Dr. Mounce has more than 10 years experience in the fields of design, operations, and safety relative to transportation engineering. Among many notable publications, his 1976 study, "Driver Visual Performance During Rainfall," is the definitive work in that field.

ERIC F. NORDLIN is a Transportation Engineering Consultant in Sacramento, California. He was formerly Chief of the Structural Materials Branch (1962-1982), and has held various other engineering positions with the California Department of Transportation since 1946. Mr. Nordlin is an expert in the design and testing of highway appurtenances and other safety improvements. He received his BS degree in Civil Engineering from the University of Minnesota in 1942.

ROBERT M. OLSON is a Professor of Civil Engineering and a Research Engineer at Texas A&M University and has been active in the Texas Transportation Institute at management and research levels during his 30-year career. He received the National Safety Council Metropolitan Life Award in Accident Prevention in 1966 for his work in the development of breakaway signs, and he has authored several definitive works for the National Cooperative Highway Research Program of the National Research Council, including the definitive 1970 work on bridge rails (NCHRP Report 86). An outstanding professor, he has received the Faculty Distinguished Achievement Award in Teaching. Professor Olson acted in the capacity of editorial consultant for this report on roadway discontinuities.

HAYES E. ROSS, JR. is a Research Engineer at the Texas Transportation Institute and a Professor of Civil Engineering at Texas A&M University. He received his Ph.D. in Civil Engineering from Texas A&M University in 1970. Dr. Ross, active in highway and roadside safety since 1966, has been engaged in numerous research activities that were brought together in the 1977 AASHTO Barrier Guide. Currently he is preparing the definitive work on roadside safety. He is a member of the key national committees concerned with roadside safety, including those with the American Society of Civil Engineers, the National Safety Council, and the Transportation Research Board. Dr. Ross was recently appointed chairman of Transportation Research Board Committee A2A04 (Committee on Safety Appurtenances).

JAMES C. WAMBOLD is Professor of Mechanical Engineering and Acting Director of the Automotive Research Program at the Pennsylvania Transportation Institute, Pennsylvania State University. He has had 3 years of industrial experience between 1958 and 1963 with Sandia Laboratories. Professor Wambold received his Ph.D. in Mechanical Engineering from the University of New Mexico in 1967. In the field of random vibrations, he is active in road-vehicle interaction and has considerable expertise with road roughness and its effects on vehicle dynamics. Professor Wambold is an active member of the Transportation Research Board, serving on Committee A2B07, and of ASTM, serving on Committee E17. He is on the executive committee of E17 and is chairman of subcommittee E17.33 on Methodology of Road Roughness.

E.A. WHITEHURST is a Professor of Civil Engineering at Ohio State University, Columbus, Ohio. He received his MA in Civil Engineering from Purdue University in 1951. He is a former director of TRANSPLEX at the Ohio State University Field Test and Evaluation Center at East Liberty, Ohio. He has been engaged in skid-resistance research since 1952. For the past 15 years he was director of the annual testing program on winter driving hazards. Professor Whitehurst was the first chairman of ASTM Committee E17. He was presented the Tilton E. Shelborne Award for skid-resistance research in 1982.

RICHARD A. ZIMMER is a Research Instrumentation Specialist with the Texas Transportation Institute. He is also Manager of Proving Ground Operations at the Research and Extension Center. He has more than 15 years experience in all aspects of highway safety research, from designing equipment and test methods to project administration. Mr. Zimmer conducted two key studies affecting this report: "The Influences of Roadway Surface Holes on the Potential for Vehicle Loss of Control," and "Pavement Edges and Vehicle Stability--A Basis for Maintenance Guidelines." He has been instrumental in developing and reviewing standards relating to traveled surfaces and tires for more than 10 years through ASTM.