CHAPTER 6 Water Accumulations

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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.

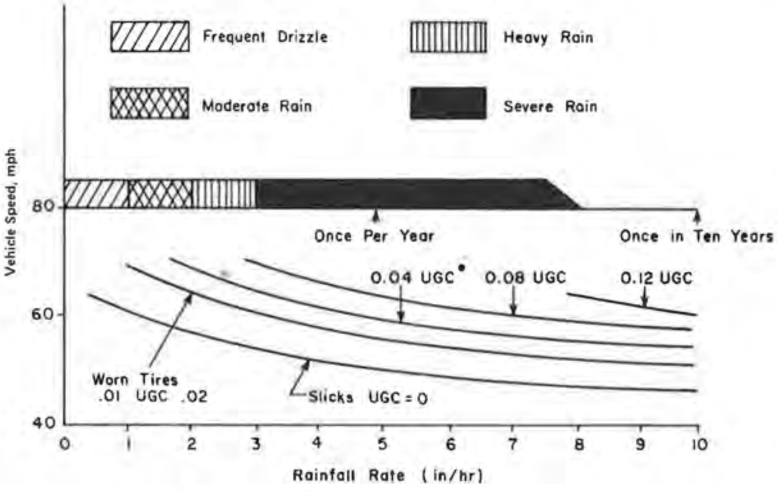
Hydroplaning of pneumatic-tired vehicles has been divided into three categories by Horne (1): viscous hydroplaning, dynamic hydroplaning, and tire-tread rubber-reversion hydroplaning. Viscous and dynamic hydroplaning are the important types of hydroplaning encountered by passenger cars. Tire-tread-reversion 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.

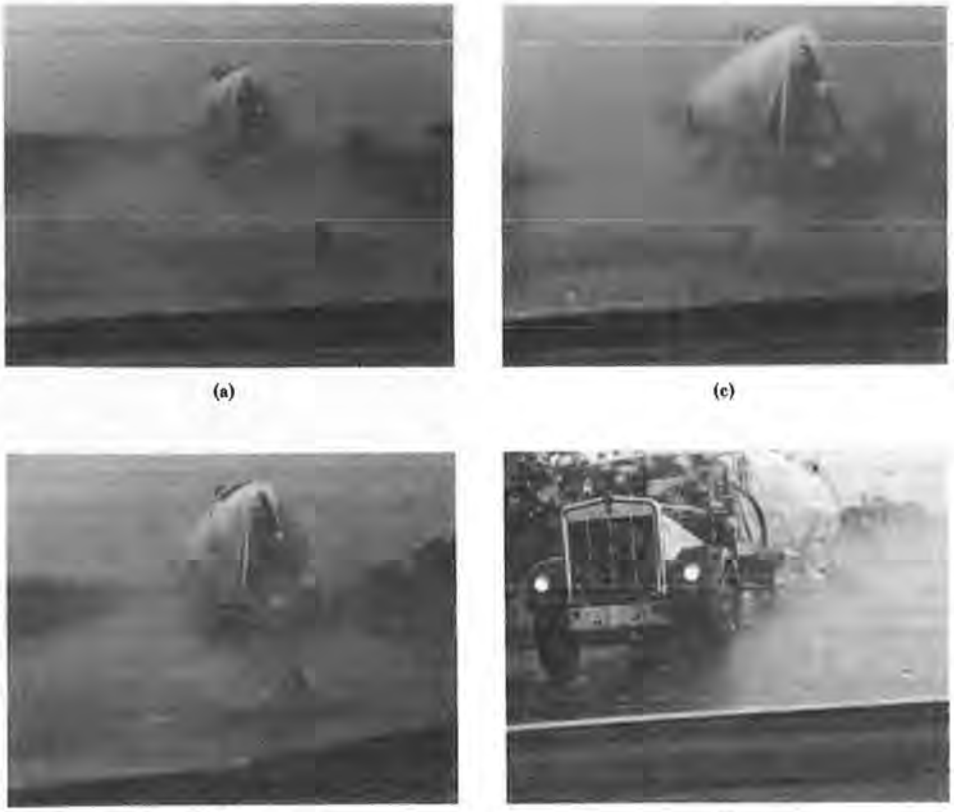
Visibility

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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