HYDROPLANING AND ROADWAY TORT LIABILITY

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ABSTRACT

Tort claims against highway agencies for alleged incidents of hydroplaning due to roadway defects have been growing in number. Many claims of hydroplaning cannot be substantiated by the weather, roadway, and vehicle conditions present at the time of the accident. And often when hydroplaning does occur, the evidence indicates that an inappropriate response to adverse driving conditions, or simply driver negligence, may be the direct cause rather than a roadway defect. Research of the phenomena of hydroplaning was reviewed to address issues which arise when hydroplaning is alleged in roadway tort litigation.

Hydroplaning is the separation of a rolling or sliding tire from the roadway surface by a layer of fluid. Of the three types of hydroplaning commonly recognized, highway engineers are primarily concerned with viscous and dynamic hydroplaning. Of these two, dynamic hydroplaning presents the greatest risk. In the extreme situation of full dynamic hydroplaning, complete separation of the tire from the pavement by a fluid layer negates the driver's ability to control vehicle speed and direction.

Hydroplaning may be avoided by consideration of several factors. Proper highway design may reduce hydroplaning risks by providing adequate pavement texture and cross slope. However, ultimate responsibility for avoiding hydroplaning lies with the driver. Drivers can reduce incidents of hydroplaning by maintaining tires in good condition at rated inflation pressures and by slowing down during rainstorms or on wet roadways.

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INTRODUCTION

Rainfall and water present on the pavement surface influence the safety of motor vehicle operation. The latest national accident statistics, compiled through 1990, indicate that approximately 10% of all fatal crashes occur on wet pavements during rainfall (1). In Texas, approximately 28% of all accidents are categorized as occurring during rainfall and/or on wet pavements (2).

Motorists must be relied upon to recognize the degradation of their ability to operate safely brought on by diminished visibility through rainfall and reduced friction capabilities on wet pavement. Many accidents in wet weather are due to loss of vehicle control, which results from either failure to recognize or to properly respond to adverse weather and pavement conditions.

In recent years, an increasing number of tort lawsuits have been filed against street and highway operating agencies with allegations of roadway defects responsible for "hydroplaning." In the adjudication of these lawsuits, many statements have been made as to when, where, and how hydroplaning occurs. Most wet weather accidents are not caused by hydroplaning. In reality, hydroplaning is a rare event, and its occurrence is dependent on many factors. This paper is a compilation of research directed to the phenomena of hydroplaning as related to roadway tort litigation.

THE PHYSICS OF HYDROPLANING

A basic understanding of the function of pavement texture in the tire-pavement interface is critical to a discussion of the mechanics of hydroplaning. Roadway surfaces are characterized by pavement microtexture and macrotexture. Microtexture describes the degree of polishing of the pavement surface or aggregate, varying from harsh to polished (3), and is necessary to the development of frictional forces between the tire and pavement on wet surfaces. The magnitude of these frictional forces becomes greater with increased microtexture, and it is maximized at lower vehicle speeds (4). When a thin layer of water is present, asperities on the pavement surface break through the waterfilm to enable direct contact between the tire and pavement (5). These asperities are thousands of small, pointed projections which comprise microtexture. High local bearing pressures are generated by contact between the tire tread and the pavement asperities, thereby allowing the tire to establish essentially "dry" contact with the roadway (6).

Macrotexture describes the size and extent of large-scale protrusions from the surface of the pavement, varying from smooth to rough. Macrotexture is a function of aggregate gradation, the pavement construction method, and special surface treatments such as grooving or chipping (3). Whereas microtexture governs wet friction at low vehicle speeds, macrotexture is the critical factor for higher vehicle speeds. Friction levels are observed to be significantly lower for pavements with poor macrotexture than for pavements with good macrotexture when vehicle speeds are high and flooded conditions prevail. This is explained by the fact that macrotexture provides channels for drainage, thereby reducing hydrodynamic pressures which exist between the tire and pavement when water is present (4). For a thin waterfilm and high vehicle speeds, macrotexture is vital to establishing and maintaining contact between the tire and pavement. For a flooded pavement, it operates as escape channels for bulk water drainage from beneath the tire footprint (6).

The physical phenomena of hydroplaning is the separation of a rolling or sliding tire from the roadway surface by a layer of fluid. On a wet or flooded pavement, hydrodynamic pressures increase as vehicle speed increases, and eventually reach a critical point at which the tire is lifted away from the surface (7). Three types of hydroplaning have been identified: (a) viscous hydroplaning; (b) dynamic hydroplaning; and (c) tread rubber reversion hydroplaning. Viscous and dynamic hydroplaning are of concern when examining highway operations on wet pavements.

Viscous hydroplaning is a problem associated with low-speed operation on pavements with little or no microtexture. It results from an extremely thin film of water existing cohesively between the tire and the pavement surface due to insufficient microtexture to penetrate and diffuse the fluid layer. For this reason, viscous hydroplaning is commonly referred to as thin film hydroplaning as a means of distinguishing it from the condition of dynamic hydroplaning, which requires a comparatively thick fluid layer.

Opinions on the importance of vehicle speed to viscous hydroplaning vary. Yeager states that viscous hydroplaning is observed at vehicle speeds greater than 32 km/hr (20 mph) (8). However, Browne contends that viscous hydroplaning can occur at any vehicle speed and with any waterfilm thickness (9). The important point to note is that it may occur when vehicle speeds are very low, such as with speeds typical of city driving. The most critical factors of influence during viscous hydroplaning are the viscosity of the fluid, tire condition, and the quality of the pavement surface. It will not occur unless the tire tread depth is very shallow and the pavement has a "polished" quality. Viscous hydroplaning may be described as a rare event characterized by a bald tire operating on a mirror-smooth surface.

Dynamic hydroplaning results from uplift forces created by a water wedge driven between a moving tire and the pavement surface, as shown in Figure 1. The risk of dynamic hydroplaning is high when fluid inertial effects dominate, as with thick waterfilms found on a flooded pavement. Dynamic hydroplaning can only occur when the water accumulation encountered by the tire exceeds the combined drainage capacity of the tire tread and the pavement macrotexture for a given speed (9). For extreme conditions, it has been observed for water depths as little as 0.76 mm (0.03 inch) with bald tires on smooth, polished pavement surfaces (8).

A hydroplaning tire may experience either partial or full dynamic hydroplaning. With partial dynamic hydroplaning, only part of the tire actually rides on the surface of the water. Contact between at least a portion of the tire footprint and the pavement surface is maintained. Full dynamic hydroplaning, on the other hand, is characterized by complete separation of the tire from the pavement by the fluid layer. The occurrence of full dynamic hydroplaning represents a far greater hazard than partial dynamic hydroplaning, as the driver is unable to control vehicle steering and braking because of the loss of contact.

Speed and waterfilm thickness are the governing conditions for partial and full dynamic hydroplaning. It is difficult to identify with precision the speed at which these phenomena occur, as other variables which describe the roadway surface, the tire condition, and the driving environment must be considered. Whereas ordinary highway operating speeds and water depths may give rise to partial dynamic hydroplaning, considerably higher vehicle speeds and a very thick waterfilm, such as that produced by high-intensity rainfall, are necessary for full dynamic hydroplaning to occur (10). For most situations, the vehicle speed at which full dynamic hydroplaning is observed would be considered unsafe or not prudent for the amount of water on the roadway, assuming that the tire tread is sufficient and that the tires are properly inflated.

FACTORS INFLUENCING ROADWAY HYDROPLANING

Dynamic hydroplaning is a function of the complex interaction between many variables. For this reason, the probability of full dynamic hydroplaning is rather low (10). Factors critical to hydroplaning are depicted in Figure 2. As can be seen, the four primary effective variables are rainfall, the roadway, tire characteristics, and the driver.

Generally, hydroplaning is a low probability event because rainfall intensities necessary to flood a pavement surface are rare and of short duration (11). Furthermore, rainfall intensities of sufficient magnitude, 5.1-10.2 cm/hr (2-4 in/hr) to create sheet flooding of pavement surfaces reduce visibility even with wipers such that prudent drivers will reduce operating speeds for safety (10).

Drainage path length refers to the distance any discrete water molecule would have to negotiate to drain from a given point on the pavement surface. It is a function of the number of lanes of travel and the lane width. A typical two-lane, crowned cross-section has a nominal drainage path length of 3.66 feet. This factor is especially significant for water accumulations which result from extended drainage path lengths associated with multi-lane roadways. An investigation of potential means of decreasing the occurrence of hydroplaning concluded that minimizing the drainage path length through careful highway design and construction is an effective strategy (11). When multiple travel lanes are present, the negative impact of longer drainage path lengths can be mitigated through appropriate application of pavement cross slope and pavement texture.

Roadway factors of pavement texture and transverse cross slope are critical to controlling water accumulation and drainage. A transverse cross slope of 2.5% is desirable to facilitate adequate surface drainage for common rainfall intensities without impeding vehicle steering or lane-changing maneuvers (10).

The role of pavement texture in collecting and draining surface water from the vehicle path has already been addressed. Balmer and Gallaway (11) reported the results of an extensive investigation of applications of pavement texture to reduce the risk of hydroplaning and to improve wet traction. The use of a gritty, coarse surface texture or finish in the construction and maintenance of pavements was recommended.

Providing texture depth is also critical because deeper textures act as larger escape channels for water forced from beneath the tire footprint region. Balmer and Gallaway discovered that increasing the texture depth from 0.76 mm (0.03 in) to 3.81 mm (0.15 in) raised the speed at which dynamic hydroplaning was predicted to occur by 16.1 km/hr (10 mph), for tire inflation pressure of 206.85 kPa (30 psi), tire tread depth of 6.75 mm (8.5/32 in), and water depth of 7.6 mm (0.3 in). It was also concluded that transverse texture, aligned parallel to the cross slope direction, can be expected to provide improved overall surface drainage, improved water expulsion between the tire and the pavement, and a decrease in the forward motion of water which is responsible for creating a water wedge between the tire and pavement.

Pavement texture depth of 1.52 mm (0.06 in) or greater is the recommended minimum for roadways with high operating speeds. This will provide adequate drainage and decrease hydroplaning for normally expected rainfall rates (10). For roadways with low-speed operation, even less texture depth may be tolerable. It must be noted, however, that even under the best of design and construction conditions, storms of unusually high intensity, though rare, are likely to create flooding of the pavement surface above the texture asperations.

The tire is one of the most critical factors influencing hydroplaning. Even on a well-designed, properly-maintained roadway, a worn or under- or over-inflated tire experiences considerably higher risk of hydroplaning than does a tire in "good" shape, for normally-expected rainfall and prudent speed. Yeager (8) and Browne (9) have addressed factors of tire construction and condition which influence hydroplaning.

Tread pattern is one of these factors. Lateral and longitudinal grooves, sipes, and ribs comprise the tire tread pattern. Grooves are the deep channels that run around the circumference of the tire (longitudinal grooves) and across the tire surface (lateral grooves). They serve two principal functions. By channeling bulk water through and out of the tire footprint region, grooves help to prevent the formation of the water wedge which penetrates into the footprint region and causes dynamic hydroplaning. They also function as reservoirs for thin waterfilms squeezed from between the tire and the pavement surface, which reduces the risk of viscous hydroplaning (9).

Four parameters describe the effectiveness of the tread grooves with respect to wet traction and hydroplaning: tread depth, groove capacity, groove shape, and groove spacing. Tread depth is primarily a measure of how much tread remains on a tire after experiencing wear as a result of extended use. When the tire is worn to an extent such that the depth of tread reaches a minimum safe value, tire replacement is recommended.

The amount of surface water to be effectively handled is referred to as the tire's groove capacity. It is related to tread depth and influenced by tire construction, load, and inflation pressure. Once the amount of pavement surface water encountered by the tire tread exceeds the groove capacity, the excess water must have sufficient time to be displaced without building up in front of the tire and creating uplift pressure on the tire. Higher vehicle speeds reduce the time of displacement and increase the risk of hydroplaning.

Another determining factor of groove capacity is groove closure. The effect of groove closure is a considerable reduction of the tread's groove capacity. This phenomenon depends upon the structural properties of the tire tread, the rotational speed of the tire, and the inertial forces of the fluid layer which the tire encounters. It is a direct consequence of lateral forces acting in the tire ribs toward the longitudinal centerline of the tire footprint. Groove closure is resisted by frictional forces between the tire and the pavement. However, in the absence of these frictional forces, such as on a wet pavement, no force exists to counteract groove closure. Groove closure has been found to be less of a problem for radial tires than for bias tires (8).

Groove shape and spacing influence a tire's wet traction capabilities and performance. Groove shape is especially important for a sliding tire, as opposed to a free rolling tire (8). Wide grooves provide optimum flow characteristics and mitigate the effects of groove closure. Slight amounts of zigzag with diagonal grooves are also desirable. For a free rolling tire, groove capacity is the controlling factor, although diagonal grooves and blading help to reduce the risk of viscous hydroplaning on a smooth surface. Grooves should be closely-spaced in order to achieve peak traction performance.

Other tire factors which relate to hydroplaning and wet traction may be generally categorized as elements of the tire carcass. These include tire dimensions and flexibility. The region of contact between the tire and pavement, the tire footprint, is measured by length and tire width. As tire width increases, the width of the footprint increases. On a wet or flooded pavement, this is important because the tire will encounter and interact with a greater amount of fluid than it would have otherwise. Accordingly, the task of collecting and channeling water away from the tire footprint becomes more difficult and requires a greater length of time, and the magnitude of hydrodynamic forces acting upon the tire is greater. But while increasing the width of the contact region is potentially detrimental, increasing its length results in greater amounts of dry contact within this region. It follows that wet traction performance and safety are enhanced.

The effects of tire footprint dimensions on dynamic hydroplaning speed have recently been investigated (12, 13, 14). The tire footprint aspect ratio is calculated as the tread contact area width divided by the length of the footprint (Figure 3). It is of particular interest in analyzing the hydroplaning tendency of tractor-trailer trucks. Aspect ratios for trucks are observed to be influenced by the magnitude of the load. The footprint aspect ratio for an empty truck is considerably higher than for a loaded truck, when holding inflation pressure constant, due to shorter tire footprints for empty trucks. As explained previously, this results in less dry contact area between the tire and the pavement. Furthermore, accident statistics show that jack-knifing of empty tractor-trailer trucks on wet pavements is a significant event which may be attributed to dynamic hydroplaning. It was determined that the footprint aspect ratio is a variable which must be considered when estimating dynamic hydroplaning speeds for pneumatic tires.

Tire construction and inflation pressure govern tire flexibility. Bias ply, belted bias ply, and radial ply are the three common methods of tire construction. With respect to decreasing the potential of the tire to hydroplane, belted bias ply and radial tires are preferred. The treads of these tires have improved stability, provided by belts under the tread region. This serves to reduce tire tread wear and groove closure, and makes possible the inclusion of exaggerated tread patterns which reduce hydroplaning risks (9).

The function of tire inflation pressure in raising or lowering a tire's hydroplaning tendency is difficult to analyze and evaluate. It has been shown that in order for dynamic hydroplaning to take place, the tire surface must deform inward, toward the center of the tire. When this deformation is present, water is capable of penetrating deeper into the tire footprint to create the water wedge that can eventually lead to full dynamic hydroplaning. Higher inflation pressure improves the tire's rigidity and its ability to resist the hydrodynamic forces which cause tire surface deformation, thereby raising the speed required for hydroplaning to occur. It also counteracts the lateral forces in the tire ribs which encourage groove closure. The drawback, however, is shortening of the tire footprint and the ensuing reduction of the dry contact area between the tire and pavement. This essentially lowers the hydroplaning speed (9).

Roadway, vehicle, and environmental factors which interact to create hydroplaning have been mentioned. The driver's recognition of and response to these various factors is critical. Drivers avert hydroplaning by direct action, for instance maintaining safe speeds on wet roadways. They can also indirectly reduce the potential for their vehicle to hydroplane through a careful program of tire maintenance.

PREDICTING AND IDENTIFYING HYDROPLANING SPEEDS

Substantial effort has been devoted to the development of formulas and criteria to identify the precise speed at which hydroplaning occurs. The most common approach has been to calculate the critical speed required for dynamic hydroplaning. Some of these equations are simple relationships which define the hydroplaning speed as a function of one or two variables. Others are considerably more complex. As might be expected, the task of predicting when hydroplaning will occur, or of identifying a particular wet-weather accident as a hydroplaning incident, is rather difficult and involves a substantial degree of uncertainty. The purpose of this section is to briefly describe some of the analytical and empirical techniques for evaluating hydroplaning potential.

In the case of viscous hydroplaning, Equation (1) describes the minimum hydroplaning speed for a pavement surface with slight microtexture:

$$V_H \geq \frac{L}{\Delta T_{sf}} . \tag{1}$$

Here, V_H is the minimum viscous hydroplaning speed, L is the length of the tire footprint region, and ΔT_{sf} is the time required for sufficient reduction of the fluid film for contact between the tread rubber and the pavement asperities to occur (9). This formula is not applicable to dynamic hydroplaning.

Yang has proposed an analytical equation to define hydroplaning as part of an effort to develop design criteria for runway pavement grooving (15). The underlying principle for this equation is that hydroplaning will occur when the water escape velocity due to an external force, the tire pressure, is less than the speed at which the surface water travels sideways. The critical moment at which hydroplaning occurs is defined by Equation (2):

$$cp^{1/2} = 0.1292 \left[\frac{\pi \ a \ v}{b} \right] , \tag{2}$$

where c is a constant, p is the tire inflation pressure (kPa), a and b describe the width and length, respectively, of the tire footprint (cm), and v is the vehicle velocity (cm/sec). For U.S. customary units, Equation (2) is rewritten as:

$$c\, p^{1/2} = \frac{\pi\, a \,/\, 4}{2\, b \,/\, v}, \tag{3}$$

where c is a constant, p is the tire inflation pressure (lbf/in^2), a and b describe the width and length, respectively, of the tire footprint region (in), and v is the vehicle velocity (in/sec). The development of this equation assumes an elliptical tire footprint shape.

One of the most frequently cited hydroplaning equations was developed by NASA engineer Walter Horne to predict the minimum dynamic hydroplaning speed for pneumatic tires (16). In its simplified form, this equation is written:

$$V_H = 6.35 \sqrt{p}, \tag{4}$$

which yields the minimum tire hydroplaning speed V_H (km/hr) as a function of the tire inflation pressure p (kPa). In U.S. customary units, Equation (4) is given by:

$$V_P = 10.35 \sqrt{p}, \tag{5}$$

where the minimum tire hydroplaning speed V_P is in mph and the tire inflation pressure p is given in lbf/in^2. The formula is derived from empirical data and based on inertial properties of the fluid layer. It is applicable to flooded pavements, when the water depth exceeds the tire tread depth.

Recent research has indicated that the minimum dynamic hydroplaning speed of automobile, truck, and bus tires varies not only with the inflation pressure, but also with the tire footprint aspect ratio (12, 13, 14). Consequently, Horne proposed a modification to his earlier formula to account for the influence of the footprint aspect ratio under load. Simplified, this new equation may be written as Equation (6):

$$V_H = 4.87 \sqrt{p \ (w/l)^{-1}} \ , \tag{6}$$

where w/l is the tire footprint aspect ratio, the tire inflation pressure p is in kPa, and the minimum tire hydroplaning speed V_H is in km/hr. For U.S. customary units, Equation (6) may be written as:

$$V_P = 7.95 \sqrt{p \ (w \ / \ l)^{-1}} \ , \tag{7}$$

which yields the speed V_P in mph as a function of the tire inflation pressure p in lbf/in^2. It is seen that the magnitude of the minimum dynamic hydroplaning speed increases as the tire inflation pressure increases and the tire footprint aspect ratio decreases (12). Research at the Texas Transportation Institute (TTI) investigated the validity of Horne's predictions of dynamic hydroplaning of lightly-loaded truck tires at typical highway speeds (13). TTI engineers formulated the relationship:

$$V = 24.99 \ (p)^{0.21} \left(\frac{1.4}{w/l}\right)^{0.5} , \tag{8}$$

normalized for the test aspect ratio of 1.4. In U.S. customary units, Equation (8) is written as:

$$V = 23.3 \ (p)^{0.21} \left(\frac{1.4}{w/l}\right)^{0.5} . \tag{9}$$

Although equations (8) and (9) differ from equations (6) and (7), they yield curves which agree closely over the range of test conditions.

A study by Gallaway, et al. developed an empirical formula for dynamic hydroplaning speed when the waterfilm thickness exceeds 0.10 inch (17). Multiple linear regression yielded the expression:

$$V = 0.902\ SD^{0.04}\ P^{0.3}\ \left(\frac{TD}{0.794} + 1 \right)^{0.06} A\ , \tag{10}$$

where A is the greater of:

$$A = \left[\frac{11.008}{WD^{0.06}} + 3.507 \right] \tag{11}$$

or:

$$A = \left[\frac{26.871}{WD^{0.06}} - 6.861 \right] TXD^{0.14}, \tag{12}$$

and V is the vehicle speed (km/hr), SD is the spindown percentage, P is the tire inflation pressure (kPa), TD is the tread depth (mm), WD is the water depth above the pavement asperities (cm), and TXD is the pavement texture depth (cm). In order to indicate the point at which hydroplaning occurs, the spindown parameter was used. Spindown describes the change in a free rolling tire's rotational velocity upon loss of contact with the pavement surface, as in full dynamic hydroplaning. When U.S. customary units are used, Equation (13) is applied:

$$V = SD^{0.04}\ P^{0.3}\ (TD + 1)^{0.06}\ A, \tag{13}$$

where A is the greater of:

$$A = \left[\frac{10.409}{WD^{0.06}} + 3.507 \right] \tag{14}$$

or:

$$A = \left[\frac{28.952}{WD^{0.06}} - 7.817 \right] TXD^{0.14}, \tag{15}$$

and V is expressed in mph, P is in lbf/in^2, TD is given as 32nds of an inch, and WD and TXD are expressed in inches.

Two studies conducted at The Pennsylvania State University have investigated hydroplaning speeds. Agrawal, et al. (18) ranked highway pavement performance by evaluating the hydroplaning potential of various pavement treatments. The dynamic hydroplaning speed was determined indirectly by measuring the brake force coefficient, the friction value that describes the tire-pavement interface. It was assumed that full dynamic hydroplaning occurs when the brake force coefficient is zero.

Huebner, et al. (19) developed a hydroplaning model which draws upon the work of both Gallaway and Agrawal. For waterfilm thicknesses greater than 0.25 mm (0.10 in), Gallaway's equation for the critical dynamic hydroplaning speed was adopted. A regression of 18 data points collected by the Agrawal study for waterfilm thicknesses less than 0.25 cm (0.10 in) was performed. The relationship:

$$HPS = 53.34\ (WFT)^{-0.259} \tag{16}$$

was obtained for the dynamic hydroplaning speed HPS (km/hr) as a function of the waterfilm thickness WFT (cm). In U.S. customary units, the equation is written:

$$HPS = 26.04\ (WFT)^{-0.259} \tag{17}$$

for the dynamic hydroplaning speed HPS in mph and the waterfilm thickness WFT in inches.

The study noted that considerably more data are required to accurately establish this relationship for waterfilm thicknesses less than 0.25 cm (0.10 in). However, the critical hydroplaning speed under this condition is much higher, and full dynamic hydroplaning speed is less likely to occur for waterfilms of this depth at legal highway speeds.

LIABILITY FOR HYDROPLANING

All of the previously discussed factors - tire inflation pressure, tread depth and design, pavement texture depth, pavement slope, drainage path length, and rainfall intensity - influence hydroplaning occurrence. But the recognition of environmental conditions creating sufficient water depths on the pavement for the possibility of hydroplaning, and the action of sustaining a reasonable operating speed under those conditions, is the responsibility of the driver.

Loss of control due to high or unsafe speed is the direct cause of most wet weather accidents. If the driver chooses to ignore high intensity rainfall and continues to operate at speeds which are considered high for the existing conditions, the probability of dynamic hydroplaning is increased. And with full dynamic hydroplaning, the driver loses control over vehicle steering and braking.

Driver expectations during rainfall must be realistic and reasonable. Operating at posted speed limits greater than 80 km/hr (50 mph) under heavy rainfall places the driver at risk of dynamic hydroplaning. Citations issued by law enforcement personnel in many of these cases charge the driver with operating the vehicle at a "speed unsafe for conditions" or "failure to control speed." Highway engineers must rely upon the prudence and reasonable operation of drivers during times of rainfall or when water is on the pavement. Speed should be reduced below 80 km/hr (50 mph) to decrease the probability of full dynamic hydroplaning (10). Overt actions or reactions by braking or steering should be carefully controlled when encountering water on the pavement surface, as friction capability is significantly reduced.

Responsibility for proper tire care and maintenance also lies with the driver. Drivers must be relied upon to maintain tire inflation pressures in accordance with the manufacturer's specifications. Although the recommended inflation pressure varies for different types of tires, it is typically at or above 206.85 kPa (30 psi) for most passenger car tires. Tire care and maintenance also implies the driver's responsibility to monitor tire tread wear regularly, and to reduce the effects of tread wear on tire performance and safety by properly balancing and rotating the tires at regular intervals. Tire tread depth should be a minimum of 0.159 cm (2/32-in) in order to reduce the vehicle's susceptibility to hydroplaning and to obtain optimum wet traction performance (10).

Highway engineers have responsibility (liability) for properly designing, constructing, and maintaining the roadway pavement to adequately drain surface water from normally expected rainfalls. This includes the recognition and remediation of pavement defects, failures, or areas prone to the possibility of ponding water. However, as stated previously, under the most desirable methods of design, construction, and maintenance of a roadway for pavement surface drainage, an atypical, high-intensity rainstorm can produce sheet flooding or water ponding such that hydroplaning can occur.

Both transverse and longitudinal areas of water puddling may develop on roadways due to wheel loads and/or failure of the pavement over time. These "ruts" trap water, and are most likely to occur on flexible pavements and be of short length. Studies indicate hydroplaning can occur in these areas when the length of the rut is 9.144 m (30 ft) or greater. However, with normal cross slopes ($\leq$ 2.5%), rut depths of 0.61 cm (0.24 in) or less do not significantly contribute to a higher risk of hydroplaning (11).

Special attention must be given by highway engineers to areas on roadways prone to ponding of water under high-intensity rainfall rates. Drainage facilities should be emphasized that will rapidly collect and remove water from locations of flat or sag vertical profile which are susceptible to hydroplaning under heavy rainfall conditions.

Horizontal alignment transition areas with superelevation also may create a "flat spot" in the transverse cross section of a roadway. This is an especially critical point when little or no longitudinal slope exists to drain water away from the travelled way. Highway engineers must anticipate the possibility of ponding water on the pavement in this situation under high intensity rainfall and introduce drainage adjustments to minimize the probability of hydroplaning.

HYDROPLANING AND ROADWAY TORT LITIGATION

An increasing number of wet weather accidents have resulted in lawsuits with claims of proximate cause being water on the pavement surface inducing loss of control through hydroplaning. The allegations in this litigation may be focused in two areas: encountering sheet flooding or ponded areas of water on the pavement surface, and testimony regarding operating speed and loss of control. The following hypothetical legal cases involving hydroplaning and tort liability are presented to illustrate typical allegations versus factual evidence and failure to fulfill duties (negligence) by either the driver or the highway agency.

Case Number 1

Driver A was proceeding through a right-hand curve on a two-lane, asphalt roadway during a moderate rain shower in daylight. Just before completing the curve, Driver A lost control of the vehicle and crossed the centerline of the roadway, sliding broadside into an opposing vehicle and injuring Driver B. Driver A filed suit against the highway agency, alleging that loss of control was due to hydroplaning which resulted from a roadway defect.

At the time of the accident, the roadway curve was well-marked and signed with an advance curve warning and an advisory speed plate of 64 (km/hr) 40 mph. Radius of curvature and cross-slope (superelevation) were shown to be in compliance for the classification of roadway and posted operating speed. The pavement surface was well-travelled, yet shown to have a good coefficient of friction. No record of complaints of comparable accidents at the same curve location were found within a prior three-year period. Both vehicles were assessed in good mechanical condition, and their tires were in adequate condition and properly inflated.

Driver A testified to a pre-collision speed below 64 km/hr (40 mph). Damage to both vehicles indicated an impact speed of greater than 80 km/hr (50 mph). The alleged hydroplaning most probably would not have occurred at a speed of 64 km/hr (40 mph) or less at this site under these geometric, pavement, and tire conditions. The broadside skid was also indicative of excessive speed above that posted and critical for the curve alignment.

Case Number 2

Driver C was travelling on a rural interstate highway with a posted regulatory speed of 104 km/hr (65 mph) approaching a severe rainstorm. Upon encountering the rainfall, the vehicle ran off the roadway and impacted a tree within the divided median. Driver C sustained injuries in the collision, for which suit was brought against the operating agency alleging hydroplaning to be the cause of loss of vehicle control.

The highway was a four-lane, divided, tangent section at the point of vehicle departure from the roadway. The roadway surface had been recently overlaid with asphaltic concrete, providing a high frictional coefficient. Cross-slope at the location was measured and found to be in compliance with published criteria.

Driver C testified that he was travelling at 104 km/hr (65 mph) when loss of vehicle control occurred. Other motorists testified to reducing speed to 80 km/hr (50 mph) due to the obvious reduction in visibility and extent of water on the pavement from the rainstorm. Meteorological data indicated the rainfall intensity for the thunderstorm associated with the accident to be near 10.2 cm/hr (4 in/hr) and the cause of flooding damage.

In this case, Driver C may have lost control of the vehicle as a result of hydroplaning upon encountering water on the pavement surface of considerable depth. Driver C possibly may have left the roadway because of poor visibility, or may have lost control of the vehicle as a result of inappropriate steering or braking reactions to hydrodynamic forces. However, it is likely that this accident was the direct result of Driver C's failure to recognize and respond to adverse weather conditions. Reasonable and prudent action on the part of Driver C, in the form of a speed reduction, would have likely avoided this accident.

Case Number 3

Driver D was travelling on a two-lane, asphalt roadway entering a left-hand curve during slight rainfall. Loss of control caused the vehicle to continue in a straight-line off an embankment to the outside of the curve. Driver D alleged that water encountered on the roadway caused hydroplaning and the subsequent loss of vehicle control. Suit was brought against the operating agency for negligence in design, construction, and maintenance resulting in a highway defect.

Driver D testified that he was travelling at the posted speed limit of 88 km/hr (55 mph) at the time of the accident. The pavement surface was worn and polished with a marginal, yet adequate, coefficient of friction. The location of the water encountered was determined to be in the superelevation transition from normal, crown cross-slope to banked cross-slope (superelevation). The transverse grade of an area on the roadway in this transition was measured and determined to be less than 0.05%. This "flat" area was compounded by also being at the sag (low) point of a longitudinal vertical grade. Furthermore, evidence indicated an average of five comparable accidents per year for this site for the three years prior to the accident.

For the existing geometric and pavement conditions, it was possible for hydroplaning to have occurred due to water on the roadway for a motorist travelling at the posted speed limit under normally expected rainfall intensities. The path of departure also indicated little or no vehicle control, typical of full dynamic hydroplaning. The agency had a duty and responsibility to recognize the combination of conditions conducive to poor drainage of the roadway, and to remediate those conditions.

CONCLUSIONS

Many roadway tort liability claims are being made with little or no factual basis to substantiate allegations of hydroplaning as a causative factor. The physical phenomena of dynamic hydroplaning can only be possible at a designated minimum speed when water depth on the roadway exceeds the combined surface macrotexture depth and tire tread depth. Other factors of influence, such as tire inflation pressure and tire footprint size and shape, may adjust the calculation of the critical hydroplaning speed.

Highway engineers have responsibility for roadway factors affecting friction capability, such as pavement texture design and depth, and surface drainage, such as cross-slope, superelevation transition, longitudinal grade, and length of the transverse drainage path. Engineers must design, construct, and maintain streets and highways in a manner which ensures proper surface drainage to minimize the probability of water accumulation under normal rainfall conditions.

Motorists must also accept responsibility for their driving behavior during periods of rainfall. A reasonable and prudent driver should recognize the greater potential danger of operating a vehicle in a wet roadway environment, and reduces vehicle speed to minimize the risk of losing control of the vehicle. For most cases of full dynamic hydroplaning, and assuming adequate tire tread and proper tire inflation, the vehicle speed at which hydroplaning is observed would be considered unsafe or not prudent for the amount of water on the roadway.

Judges and juries in cases of roadway tort litigation must determine if hydroplaning did occur and its relevance as a causative factor in many accidents. In addition, assessment must be made as to responsibility for conditions which result in hydroplaning. These decisions can only be made with factual information about the physical phenomena of hydroplaning and factors of influence, of both the roadway and vehicle. Hopefully, this paper has addressed those issues relevant to hydroplaning and roadway tort litigation in an informative and helpful manner.

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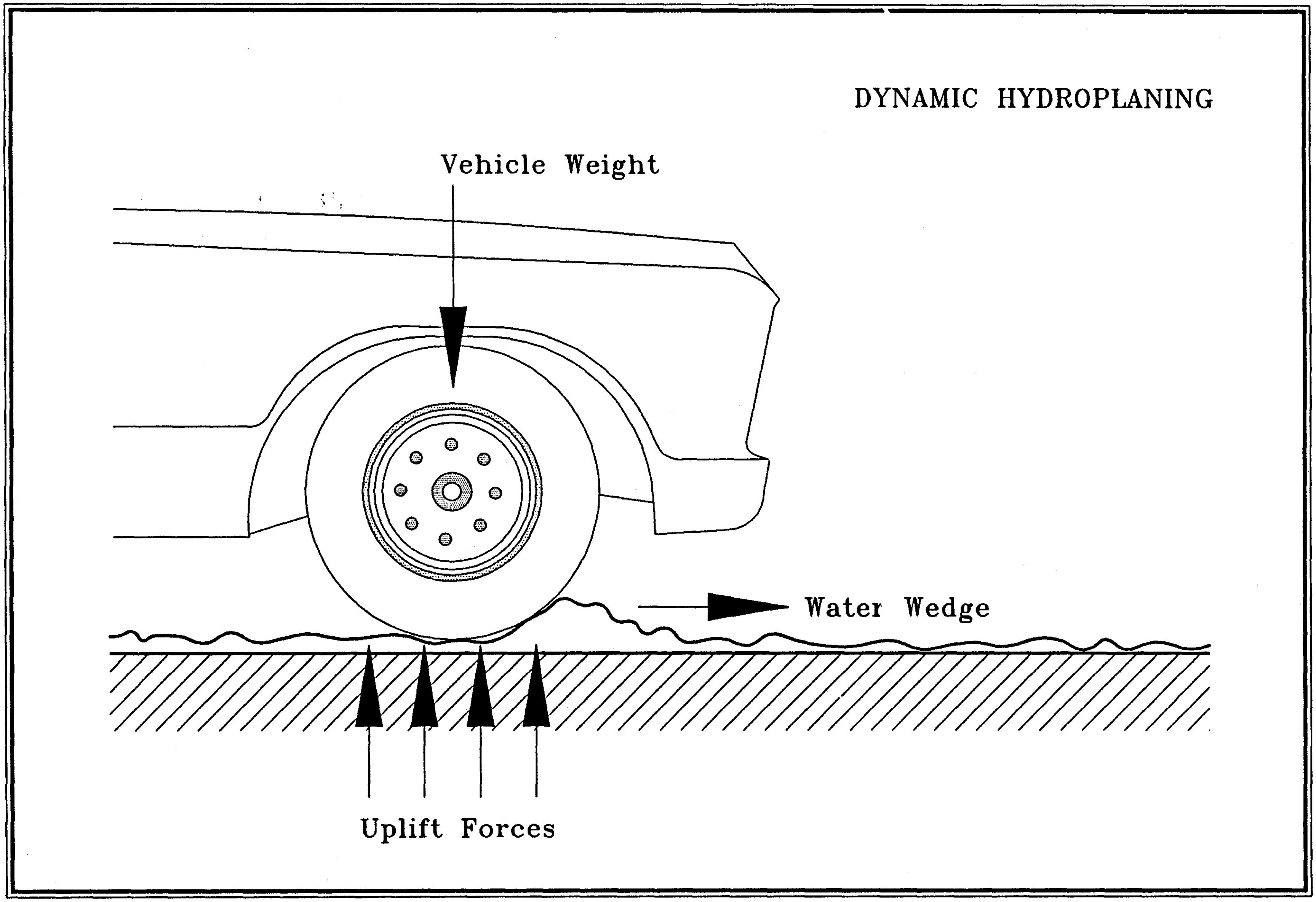
DYNAMIC HYDROPLANING
Vehicle Weight
Water Wedge
Uplift Forces

Figure 1

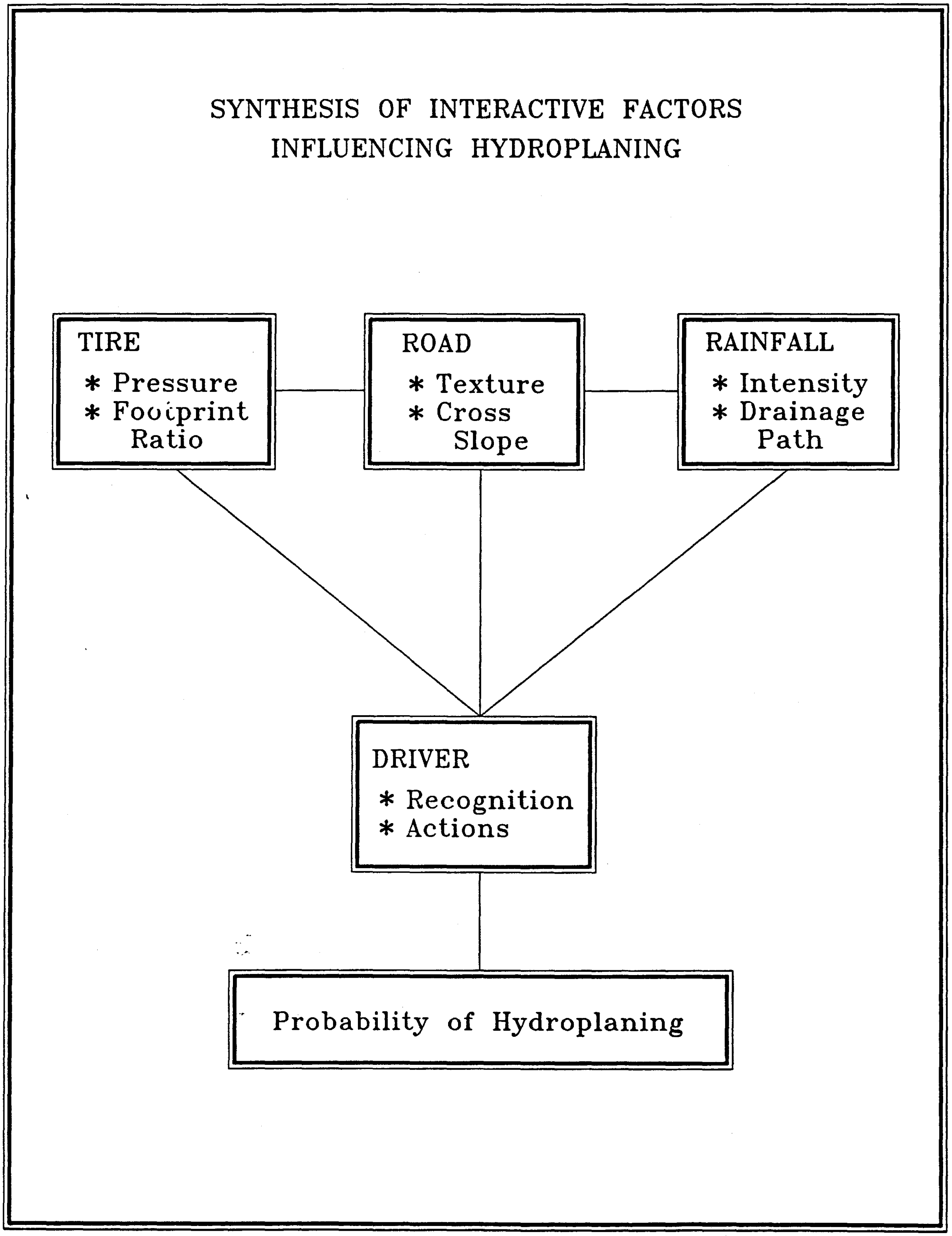
SYNTHESIS OF INTERACTIVE FACTORS
INFLUENCING HYDROPLANING
TIRE
* Pressure
* Footprint Ratio
ROAD
* Texture
* Cross Slope
RAINFALL
* Intensity
* Drainage Path
DRIVER
* Recognition
* Actions
Probability of Hydroplaning

Figure 2

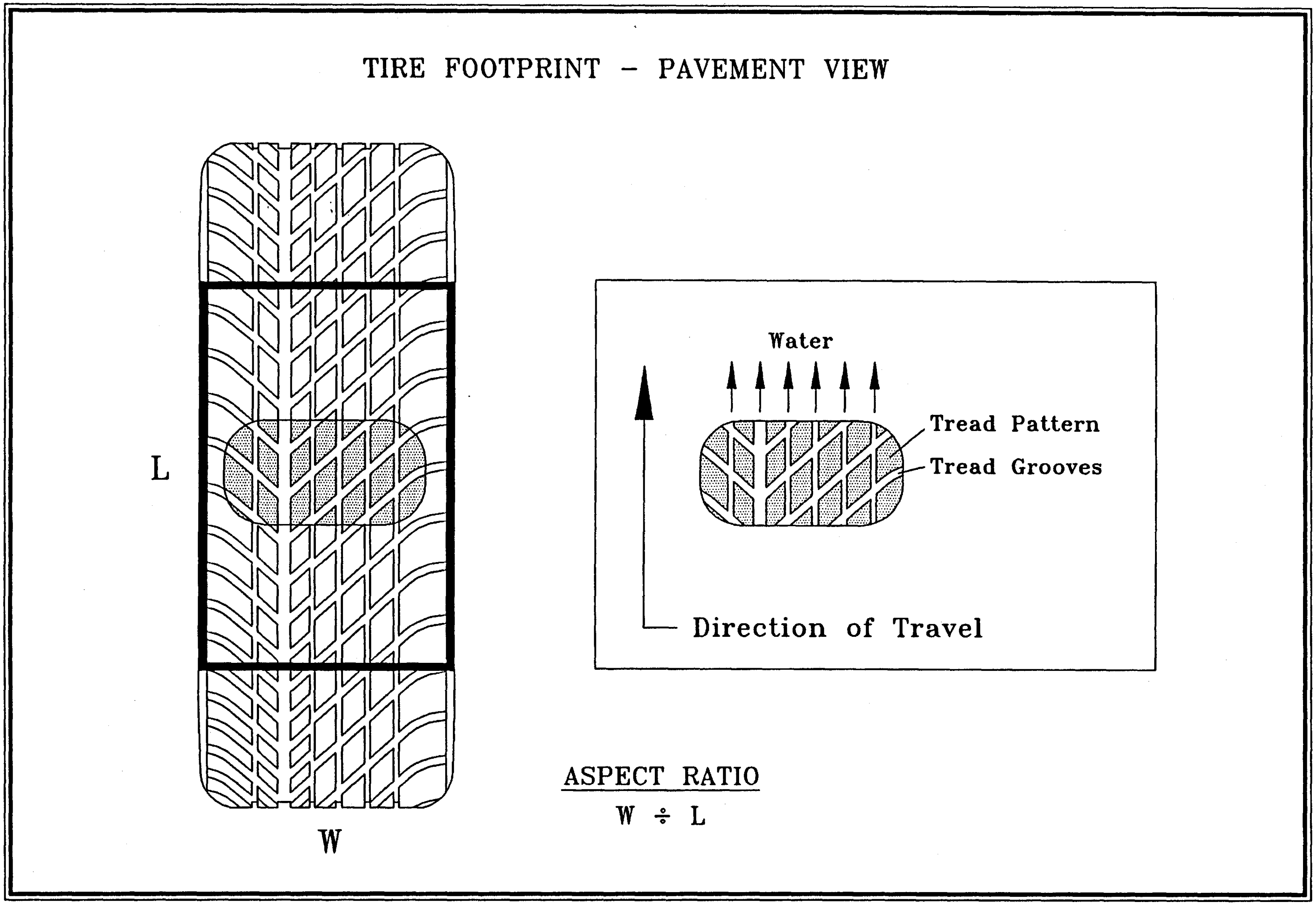
TIRE FOOTPRINT - PAVEMENT VIEW
L
W
Water
Tread Pattern
Tread Grooves
Direction of Travel
ASPECT RATIO
W ÷ L

Figure 3