Water op de weg en verkeersveiligheid
Water on the road and traffic safety

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Samenvatting

Water op de weg heeft een negatieve invloed op de verkeersveiligheid, om de volgende redenen:

- De stroefheid van een nat wegdek is lager dan van hetzelfde wegdek als het droog is.
- Bij toenemende waterdikte op de weg en toenemende verkeerssnelheid krijgt een band steeds minder grip op de weg (dus lijkt het wegdek een steeds lagere stroefheid te krijgen) en kan die grip zelfs helemaal verliezen. De band gaat als het ware waterskieën. Dit staat bekend als aquaplaning.
- Water op de weg wordt weggespoten en opgestoven door de banden van het verkeer, waardoor het zicht voor het achterliggende verkeer vermindert.

Deze bijdrage beschrijft de resultaten van een literatuurstudie, uitgevoerd voor RWS, naar een kwantificering van bovenstaande fenomenen.

Summary

Water on the road has a negative impact on traffic safety, for three reasons:

- The skid resistance of a road surface is less in wet condition, than when dry.
- With increasing water thickness and increasing vehicle speed, a tyre gets decreasing grip on the road (as if the road shows decreasing skid resistance) and may even lose grip altogether. In that case the tyre goes waterskiing, sort of. This is called aquaplaning or hydroplaning.
- Water on the road is squeezed away by the vehicle tyres, into jets and droplets (“splash and spray”), which reduce visibility for other traffic.

This paper gives some results of a literature survey, commissioned by the Dutch Highway Authority (RWS), into quantification of these phenomena.

Trefwoorden

Verkeersveiligheid, aquaplaning, stroefheid, spat en stuifwater, regenwaterafvoer,

Key words

Traffic safety, hydroplaning, skid resistance, splash and spray, road surface drainage

1 Introduction

A water film of less than 0.1 mm up to several centimetres thickness, e.g. due to rainfall, on a road (or airfield) pavement decreases traffic safety by a number of mechanisms:

- Reduced friction coefficient between tyre and pavement, resulting in reduced steering and braking capabilities of the traffic vehicles, ultimately leading to:
- Hydroplaning (in American English, a.k.a. aquaplaning in British) at higher vehicle speeds, where the tyre fully loses contact with the pavement due to a water wedge between the tyre and the pavement, which cannot be expelled by the tyre though the combined "outlets" of tyre tread grooves and pavement macrotexture (and possibly pavement permeability);
- Splash and Spray from the tyres of the traffic vehicles, reducing visibility for other drivers.

In the Dutch Motorway Pavement Design Guide [RWS 2006], geometric design criteria are given, which aim to limit the water film thickness to 2.5 mm, given a certain rainfall intensity during a certain period. This limit value is based on Dutch studies in the 1970's on dense (non-permeable) pavement surfaces.
Presently, however, more than 80% of Dutch Motorways has a Porous Asphalt (PA) surface, either 50 mm PA 16 or 70 mm two-layer PA. The question was raised whether the limit value of 2.5 mm water film thickness still is the optimal value for these permeable surfacings. It seems likely that (at identical water depth above the pavement asperities) friction coefficients and hydroplaning speeds may be higher on permeable surfacings, relative to non-permeable pavements. This is because on PA the water has an extra "outlet" through the pavement, in addition to the common outlets of pavement macrotexture and tyre tread pattern.

Also, the calculation of the water film thickness on a PA is more complicated than on a non-permeable surface, because of the combination and interaction of the following phenomena:

- Vertical flow into the PA,
- Storage in the PA,
- Horizontal flow through the PA,
- Horizontal "surface flow" through and over the hydraulic "rough" PA macrotexture.

A literature study was done, focussing on the influence of the water film thickness on highway traffic safety, through its influence on friction coefficient and hydroplaning speed, as influenced by pavement macrotexture and permeability, but mainly disregarding Splash and Spray.
In the literature search, no data were found on crash studies, directly relating accident risk to water film thickness, mainly because water film thickness data generally are not available. Generally, the approach in literature has been to model water film thickness and then relate hydroplaning speed to that thickness. The water film thickness typically is found to be depending on rainfall intensity, pavement geometry and pavement texture depth or pavement hydraulic roughness.

Water film thickness is critical at pavement cross-slope transitions, where cross-slope changes direction from positive to negative or reverse. These transitions may occur at the beginning and end of horizontal curves in the roadway, and where horizontal curves in roads change direction. These transitions are critical, because they contain locations where cross-slope is zero, and therefore a thicker water film will occur. These may be slightly lessened by applying a longitudinal slope to the cross-slope transition. Other critical locations with high water films may be depressions in the pavement surface. These may be local, like e.g. rutting, or larger, like the bottom of a valley between two hills.

Hydroplaning risk is lessened if drivers reduce their speeds under high precipitation. This is known to occur, but often the speed reduction is less than it should be for safety reasons.

2 Tyre-water-pavement interaction

An extensive review of the hydroplaning and wet friction phenomena can be found in Srirangam (2015). Some aspects will be detailed below.

When a tyre travels on a wet pavement surface, the load on the tyre will try to squeeze the water from the tyre-pavement interface. Since the 1970's, often a three-zone model is used, as shown in Figure 1. The front part of the tyre in zone 1 floats on an unbroken, thin film of water. Farther back, in zone 2, the tyre is able to drape over the larger asperities of the road surface and will begin to make actual contact with the smaller asperities. In zone 3, only a thin film of water may remain, and in this area the tyre makes contact with the surface through the film. The relative size of these three zones depends on tyre contact area and contact pressure, speed, water depth and the combined draining abilities of tyre tread grooves and pavement macrotexture (and possibly pavement permeability). Above a critical speed (relative to the other factors) there may be no contact with the pavement, and hydroplaning occurs, where the entire tyre is supported by the water.

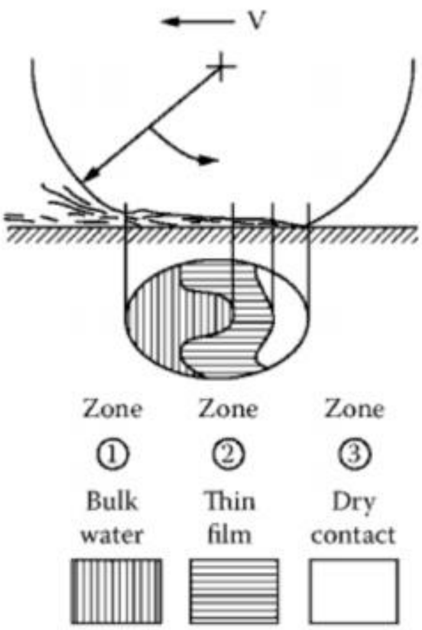


Figure 1 Three-zone concept for tyre-water-pavement interaction [Flintsch et al. 2014]

3 Water film thickness

The water film thickness depends on a number of factors:

- The water supply, which in turn depends on:
  - The rainfall intensity
  - The rainfall duration, especially when this is shorter than the time required to achieve ‘steady state’ conditions.
  - The upstream “catchment area” draining through a specific point, which itself depends on:
    - pavement width (or distance from pavement crown or upper edge)
    - combination of pavement cross-slope and longitudinal slope, especially:
      - in areas with zero cross-slope, where a pavement changes direction of cross-slope because of a change in horizontal curvature direction (cross-slope transitions), or
      - at the bottom of a dip in the longitudinal profile, where there is much longitudinal inflow, but no longitudinal outflow.
  - The pavement storage capacity for rainwater, mainly dependent on
    - Volume of water-accessible air voids in the friction course [1]
    - Layer thickness of the friction course
    - Vertical permeability of the friction course
  - The pavement subsurface horizontal drainage capacity, depending on
    - Thickness and horizontal permeability of the PA (including clogging)
    - Slope (combination of cross-slope and longitudinal slope)
  - Any drainage facilities in the flow surface (e.g. drains between driving lanes)
- The combination of pavement cross-slope and longitudinal slope
- Any unevenness in the pavement, like e.g. rutting, which obstructs free flow in some directions
- The pavement “hydraulic roughness” (as a measure of the resistance to surface flow)
- The pavement texture depth (as a reduction to the water depth above the pavement asperities), also influencing the hydraulic roughness

At slope transitions, flow lines will be curved and non-parallel. In those areas, the “catchment area” for a certain “point of unit width” is not simply its upstream length times unit width, but influenced by converging or diverging flow lines, modelling of which can be done numerically, and sometimes analytically.

When water can flow into and through a porous pavement, surface flow is complicated by the subsurface flow. Two simplifications are often used to describe this phenomenon.
The first assumes that the porous pavement is not yet saturated and that vertical inflow occurs, described by the pavement permeability. Then, the “net rainfall” or “excess rainfall” intensity is calculated by subtracting the vertical inflow from the rainfall intensity.
The second assumes that the porous pavement is fully saturated and does not contribute to the drainage, so the full rainfall intensity must drain in surface flow.
The first assumption will only be true in the early stages of a rainstorm, and the latter assumption does not fully cover the complex interactions of surface and subsurface flow, but is often considered to be a good approximation.
In this study, only the Perfcode software, developed by Eck et al. (2010), was identified as coupling surface and subsurface flow.

[1] Several researchers (e.g. Welleman 1977) have shown that not all voids in PA are accessible to water. Accessibilities of 50-70% were found. Also, accessibility of air voids to water and permeability of PA can be variable over time, especially when changing from dry to wet conditions, because of the possible presence of any hydrophobic clogging.

NB Some researchers define water film thickness as the depth above the pavement asperities (so the water in the pavement texture depth is neglected), whereas others regard the nominal water film thickness, such as would be present on a completely smooth pavement surface. The difference between both is the water film thickness in the texture depth, which may be up to about 2 mm.

To fully incorporate all the influences mentioned above, dynamic flow calculations in 3D space and time may be necessary. Often, more simple solutions may be adequate, such as formulas for water depth on straight flow paths..

Several researchers (e.g. Gallaway et al 1979, Charbeneau et al 2008, and Flintsch et al 2014) have reported the results of flume experiments, where water film thickness was measured on straight one-directionally sloped surfaces under different conditions of water inflow, both surface inflow and simulated rain. Different types of surfaces were tested, both “real” pavements and more artificial surfaces. Wide ranges of rainfall intensities and flow lengths were tested.

It should be noted that the often used PAVDRN formula for predicting water thickness , at least as published by Anderson et al. (1986), was found to deviate strongly from most other formulas, indicating that its formulation is probably erroneous (Gunaratne et al. 2012)

At water film thicknesses over about 2 mm, many formulas are in reasonable agreement. However, under 2 mm the different formulas may differ considerably, partly because of the way the texture depth is taken into account.

For instance, Flintsch et al (2014), referring to earlier work, produce a generic form for the water depth formula, which they fitted to their flume experiment data, resulting in the following formula:

$$d = 6x10^{-4}\ T^{0.09}\ (LI)^{0.6}\ S^{-0.33}$$

where:
d = water film thickness above the pavement asperities (m)
T = texture (mm)
L = drainage length (m)
I = rainfall intensity (m/h)
S = slope (ratio)

Although Flintsch et al consider the water depth above the pavement asperities, their formula always produces positive values, even for very low rain intensities that would flow inside the pavement texture. Other researchers take this into account, by subtracting the texture depth from the total water depth.

Also several numerical models were developed to calculate the water thickness on pavements of various textures and geometries, under different rainfall intensities. These models partly differ in the hydrological theories and approximations that they use to model the surface flow. Many of the numerical models (software programs) found in literature could not be acquired within the study.

Only one model was found that specifically combines subsurface flow through Porous Friction Course (like PA) with sheet flow over the surface of the pavement. This is the

Perfcode program, developed by Eck et al (2010). Unfortunately this program cannot consider varying cross sections over a pavement length, and therefore cannot be used at cross-slope transitions. A few exercises were executed within the study with this program. These showed that that for a 1x/50yr Dutch rainstorm (20 mm in 5 minutes) the maximum water film thickness on top of 50 mm Porous Asphalt is almost the same as the thickness on top of a dense pavement with the same hydraulic surface roughness. It seems that the PA mainly acts like a storage buffer and does not significantly influence surface flow after the buffer is full. This would mean that water film thickness on PA may be approximated by programs that only consider surface flow, after cutting off the first part of a cumulative rain history, corresponding to the storage volume in the accessible voids of the PA.

4 Hydroplaning speeds

Literature, e.g. Srirangam (2015), gives the following influencing factors on hydroplaning speed:

- Tyre
  - Tyre pressure
  - Tyre load[2]
  - Tyre size
    - Radius,
    - Tread width
  - Tyre footprint area (size and shape, especially width/length ratio)
  - Tyre profile (drainage capacity)
    - pattern of grooves
    - groove volume relative to tread width
      - groove depth
      - number of grooves,
      - width of grooves,
  - Tyre construction (bias ply, radial ply, reinforcement pattern, etc.)
  - Tyre slip ratio or yaw angle
- Water
  - Water film thickness
  - Water viscosity (a.o.: temperature, pollutants)
  - Water density
- Pavement
  - Pavement macrotexture ("surface" drainage capacity)
    - Texture depth (sand patch or MPD)
    - Texture pattern
    - Hydraulic roughness (e.g. Manning's roughness)
  - Pavement permeability ("subsurface" drainage capacity)
    - Hydraulic conductivity (horizontal and vertical)
    - Thickness of permeable layer

Typically the following relations are accepted:

- Higher water film thickness gives lower hydroplaning speed.
- Higher tyre pressure gives higher hydroplaning speed.

[2] Tyre load was found not to have much effect, as the tyre footprint changes with changing load, to keep contact stresses approximately equal to the inflation pressure

- Higher tyre profile cross section area gives higher hydroplaning speed.
- Higher footprint aspect ratio (width/length), so wider or shorter footprint, gives lower hydroplaning speed.
- Higher pavement texture depth gives higher hydroplaning speed.

Several sources were found giving formulas for hydroplaning speeds, partly based on experiments, partly based on modelling. One set of formulas that is often used, is part of the PAVDRN software and published by Anderson et al. (1998). This is shown in Figure 2.

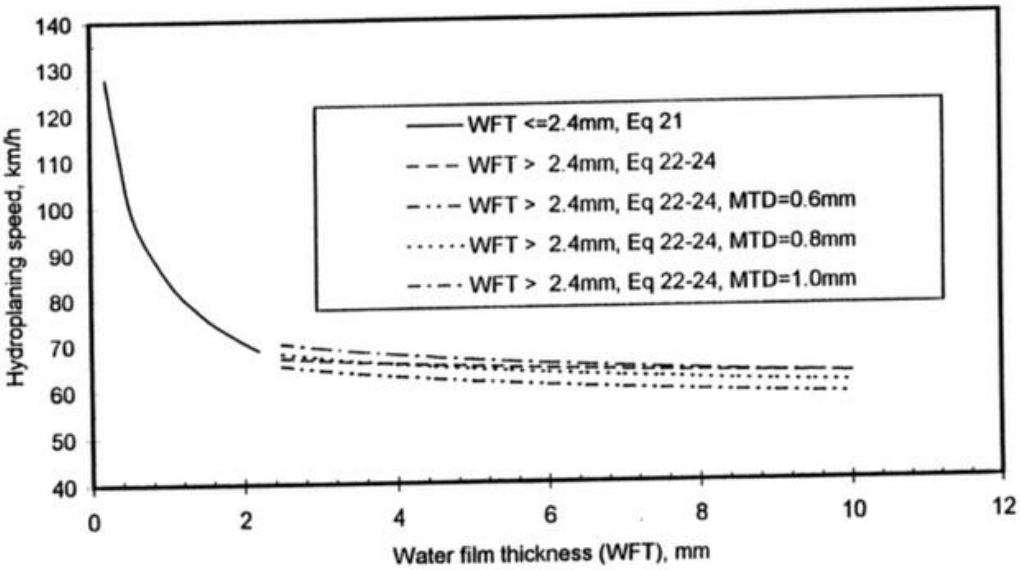


Figure 2 Hydroplaning speed formula in PAVDRN, (MTD = pavement texture depth) [Anderson et al. (1998)]

Note that the left part of the graph (for water depth <2.4 mm) is based on friction measurements with a locked wheel (smooth tyre), whereas the right part of the graph is based on experiments with a free rolling wheel (with various tread depths and tyre pressures), where spindown was measured. Although both phenomena are indications of hydroplaning, they don't describe the same phenomenon under the same conditions. Generally is accepted that hydroplaning of locked wheels will occur at lower speeds than hydroplaning of rolling wheel, all other conditions being equal.
Also note that in the right part of the graph, differences in texture depth give different hydroplaning speeds at equal water thickness. Differences in tyre pressure, tread depth or tread pattern are not considered, as a fixed tyre pressure of 165 kPa and tread depth of 2.4 mm were used in this formula.

An expansion of this work is shown in Figure 3, which does account for tyre tread depth.

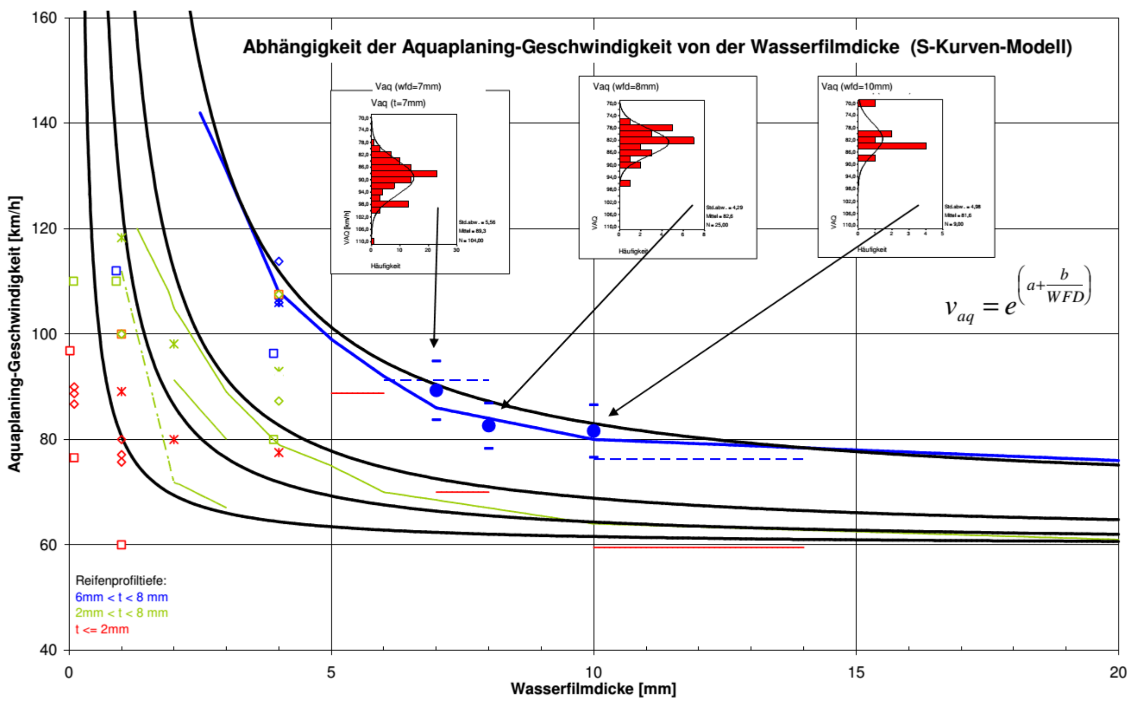


Figure 3 Hydroplaning speed model for 8, 4, 2 and 1 mm tread depth (black lines), together with experimental data of several authors (colours) and hydroplaning tests on new tyres (frequency curve inserts, summarised in graph as blue ball average and blue dash standard deviation)

5 Friction coefficient

The literature survey found some results of friction measurements with different water depths. Here, only the results of Welleman (1977) will be discussed. Other results show similar trends.

Welleman (1977) reports on Dutch measurements of the longitudinal friction coefficient at several speeds and water thicknesses on five experimental pavement surfaces. The water film thickness was achieved by artificially ponding the strip of pavement over which the measuring wheel was towed.

The tested pavement surfaces are listed in Table 1. This also lists the texture depth (TD, sand patch method) and the Pendulum Test Value (PTV, the skid resistance measured with the British pendulum).

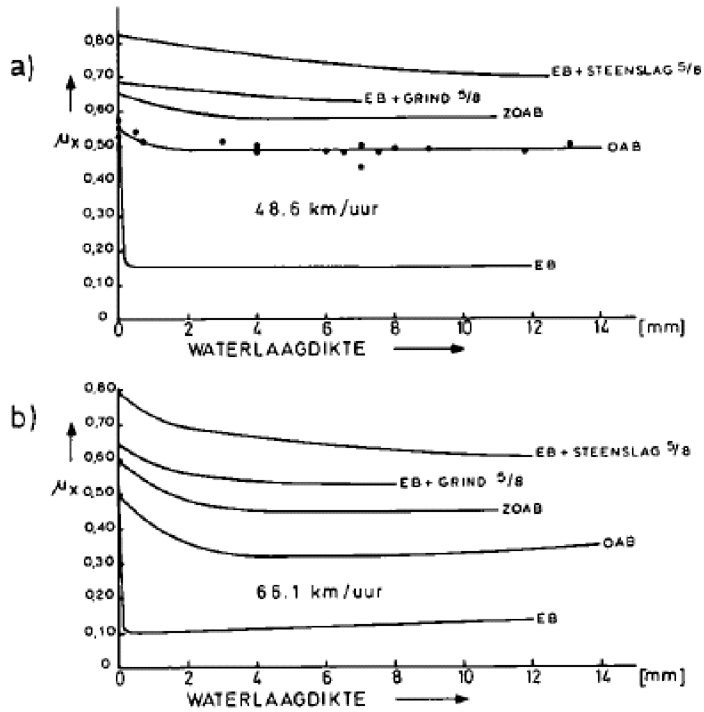
Table 1 Pavement types for friction tests [Welleman 1977]

Pavement surface	Code in graphs	TD (mm) circa	PTV
Epoxy-bitumen	EB	0	33
Epoxy-bitumen + chippings 5/8	EB + steenslag 5/8	4.3	85
Epoxy-bitumen + gravel 5/8	EB + grind 5/8	4.1	73
Porous Asphalt	ZOAB	Indeterminable	74
Asphalt Concrete	OAB	0.7-0.9	74

The friction measurement results are shown in Figure 4, for each of the measurement speeds. The figure clearly shows several things:

- A decrease in friction at increasing speeds,
- A sharp decrease of friction, at speeds of 65 km/h and over, with water film thickness increasing from 0 to about 2-3 mm.
- An gradual increase of “friction”, at speeds of 65 km/h and over, with water film thickness further increasing from about 2-3 mm. However, Welleman states that this is not real tyre-pavement friction, useful for manoeuvers, but water “drag”.
- With increasing speed, a gradual decline of the water film thickness at which the lowest friction occurs. This can be interpreted as a decreasing hydroplaning speed at increasing water film thickness.
- At all speeds and water film thickness, an increase of friction with increasing texture depth, when PA (ZOAB) is assumed to have an “effective” texture depth of about 2 mm.

Welleman concludes that changes of water film thickness in the range above about 2-3 mm barely have any effect on friction, so measures to prevent friction loss will only be effective if they reduce the water film thickness to below 2-3 mm. This should be interpreted as “as far below as possible”, because the graphs show the sharp loss of friction at lower water film thickness. Accepting a water film thickness to 2.5 mm means that all friction loss (and traffic safely loss) already has occurred. Further water film thickness increase would not make matters worse for locked tyres, although it may still worsen conditions for rolling tyres.



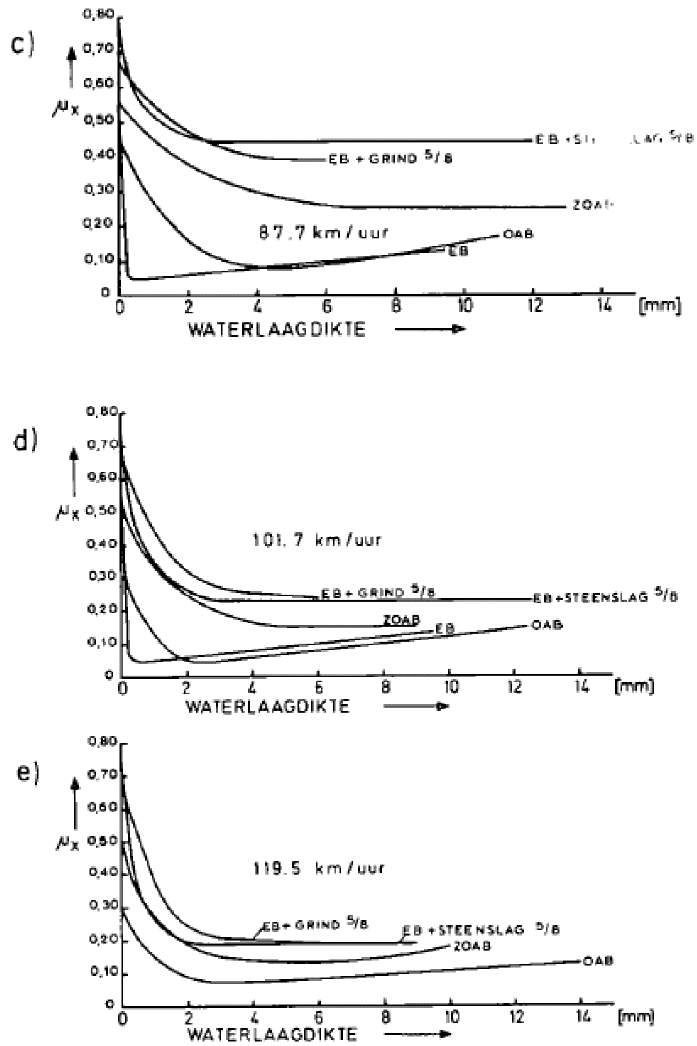


Figure 4 Wet friction coefficient μx as a function of water layer thickness over pavement asperities ("waterlaagdikte" in Dutch), for five speeds and five surfaces [Welleman 1977].

6 Splash and Spray

When vehicle tyres move through a water film on a pavement, they produce splash and spray. These are water drops and droplets in the air that reduce visibility for road users and thereby increase crash risk if drivers maintain their speeds. However, Splay and spray, although being a nuisance, could even have a positive effect on traffic safety, if it causes drivers to sufficiently lower their speed to compensate for the risk increase. At reduced speeds, also the hydroplaning risk is less, so Splash and Spray could be a useful warning to the drivers.
How the pros and cons of Splash and Spray finally add up in practice is not known.

Flintsch et al. (2014) report on a study to develop a Splash and Spray Assessment Tool. They define:

- Splash as "the mechanical action of a vehicle's tire forcing water out of its path. Splash is generally defined as water drops greater than 1.0 mm (0.04 inches) in diameter, which follow a ballistic path away from the tire."

- Spray as being formed "when water droplets, generally less than 0.5 mm (0.02 inches) in diameter and suspended in the air, are formed after water has impacted a smooth surface and been atomized."

Though splash and spray are separate processes, they are often referred to collectively because of the difficulty of monitoring and measuring them individually.

The developed tool reportedly uses six steps:

1. Compute the water film thickness based on the rainfall intensity and pavement surface properties.
2. Compute the maximum amount of water available for splash and spray based on the computed water film thickness.
3. Compute the contribution of each splash and spray mechanism (bow splash waves, side splash waves, tread pick-up, and capillary adhesion).
4. Compute the spray density corresponding to each mechanism based on the corresponding mass flow and the speed of the truck.
5. Compute the total spray density.
6. Convert the spray density level to a subjective nuisance index.

However, no information was found on the internet regarding the public availability of this Tool.

7 Conclusions

Conclusions from the literature survey, not all substantiated in this paper, are as follows.

General

- A water film on a road pavement has a negative impact on traffic safety, through the combined effects of three mechanisms:
    - Reduced friction coefficient between tyre and pavement, resulting in reduced steering and braking capabilities of the traffic vehicles, ultimately leading to:
    - Hydroplaning at higher vehicle speeds, because the tyre fully loses contact with the pavement due to a water wedge between the tyre and the pavement, which cannot be expelled by the tyre though the combined "outlets" of tyre tread grooves and pavement macrotexture (and possibly pavement permeability);
    - Splash and Spray from the tyres of the traffic vehicles, reducing visibility for other drivers.
- Of these mechanisms, friction reduction is dominant at lower water film thicknesses. Friction decreases significantly with water film increase, at values less than 2 mm, especially for smooth tyres and especially at higher speeds.
- However, many researches have focussed only on hydroplaning and have not considered friction reduction.
- No data were found giving a direct relationship between water film thickness and crash risk, Therefore, it is not possible to consider the balance between costs and benefits of lower or higher design values for maximum water film thickness.

Water film thickness prediction

- Several empirical formulas for water film thickness, as function of rainfall intensity, drainage path length, drainage slope, and surface texture, were found and compared. This yielded a fair correspondence for water depths over 2 mm, but less for small thickness. These formulas are only applicable for situations with constant drainage slope (constant longitudinal slope and cross-slope) and constant rainfall intensities. For real rainfall histories and more complex geometries, like cross-slope transitions, more advanced modelling is required.

- Water film thickness modelling has significantly increased in recent years, a.o. by the work of Charbeneau et al. (2008), Herrmann (2008), Eck et al. (2010a), Wolff (2013) and Flintsch et al (2014).
- The software programs developed by Charbeneau, Herrmann and Wolff reportedly are able to calculate water film thickness for varying rainfall intensities and pavement geometries, including cross-slope transitions. However, these programs seem to be limited to non-permeable surfacings, and were not found on the internet to be publicly available. The latter also applies to the software described by Flintsch.
- The Perfcode software developed by Eck combines subsurface and surface flow on Porous Asphalt, but cannot handle cross-slope transitions.
- Results from 2 exercises with Perfcode have shown that for a 1x/50yr Dutch rainstorm (20 mm in 5 minutes) the maximum water film thickness on top of 50 mm Porous Asphalt with 20% void content is almost the same as the thickness on top of a dense pavement with the same hydraulic surface roughness. It seems that the PA mainly acts like a storage buffer and does not significantly influence surface flow after the buffer is full. This would mean that water film thickness on PA may be approximated by programs that only consider surface flow, after cutting off the first part of a cumulative rain history, corresponding to the storage volume in the accessible voids of the PA.

Prediction of hydroplaning speed

- Several empirical formulas for hydroplaning speed, as a function of various parameters, were found and reported in the literature survey. Some were compared against each other and against modelling results.
- Many formulas describe a sharp drop of hydroplaning speeds with the first 1-4 mm water depth, with slower decrease at further increasing water depths. Such formulas are mostly related to friction loss in the first 'leg" and other phenomena (often tyre spindown) in the second "leg". There is some debate as to whether both legs really describe the same hydroplaning phenomenon.
- In general, hydroplaning speed is higher for rolling tyres, than for braking or steering tyres, all other conditions being equal.
- Although experimental studies were limited to a certain (but sometimes large) number of cases, they were converted into generalised formulas. Although advanced modelling offers opportunity to evaluate unlimited cases, until now only a limited number of results were published, which were not generalised by their authors. Therefore, no general use can yet be made of the modelling results.
- No studies were found into the influence of pavement porosity on hydroplaning speed.

Selection of design criterion for maximum water film thickness

- Given the shape of most formulas for hydroplaning speed as a function of water film thickness (a sharp drop of hydroplaning speeds with the first 1-4 mm water depth, and slower decrease at further increasing water depths), there is no "logical" value for a design criterion for maximum water film thickness. Any criterion will be more or less arbitrary, preferably based on a cost-benefit analysis. However, data for such an analysis are currently lacking.
- The first 1 to 4 mm water film thickness (on top of the pavement wearing course, either porous or not) may already cause a drop in wet friction. This increases the accident risk and hence statistical accident costs to society. However, limiting water

film thickness to below e.g. 1 mm, also under conditions of heavy rainfall like 1x/10years, is not practically feasible.

- At the present design value of maximum 2.5 mm water film thickness, the often used Gallaway formula predicts hydroplaning speeds between 80 and 110 km/h for pavements with texture depths of 1-2 mm, and passenger car tyres of 2-10 mm tread depth and 200-250 kPa inflation pressure. This is below the legal maximum speed on Dutch motorways, indicating hydroplaning risk at "normal" speeds when that water film thickness is reached or exceeded.
- Increasing that water film thickness design value to 5 mm, gives "only" 5% decrease in hydroplaning speed, whereas tyre tread depth decrease from 10 to 2 mm (new to worn) gives an 8% loss and a tyre pressure decrease from 250 to 200 kPa gives a 6.5% loss, all according to the Gallaway formula.

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