Computer Simulation of Hydroplaning Effects on Geometric Design - Optimization Strategies for Road Sections with Critical Rainwater Drainage

Wolfram Ressel
Universität Stuttgart, Germany
Institute for Road and Transportation Science
Chair for Road Design and Construction

Steffen Herrmann
Universität Stuttgart, Germany
Institute for Road and Transportation Science
Chair for Road Design and Construction

Synopsis

Heavy rainfall is a prime factor which reduces driving safety intensely. Tire grip decreases and in cases of higher water film thickness, complete aquaplaning of vehicles is likely to occur. Primarily, wide multi-lane roadways are concerned, as flow path lengths of the runoff water are high. Furthermore, typical roadway alignment types can about triple the drainage path lengths compared to “normal roadway arrangement”. These critical types are cross slope change-over and sag vertical curves, or a combination of them.

To predict the hydroplaning-performance of road sections subject to its geometric design and surface roughness, a computer model was developed. The model is based upon on a discrete surface-model. Upon this surface, one-dimensional rainwater runoff paths are generated. For each flow path the water film thickness is calculated by a one-dimensional finite volume scheme. The intermediate range between the flow paths is filled by an interpolation algorithm. As result, the water thickness for each mesh is given. On this calculated water film thickness topography, fictitious vehicle lanes were applied. The water film traces or hydroplaning speed traces under these lanes are the basis for the valuation of the hydroplaning-performance.

The model is intended for use in the geometric design process of new pavements as well as in the elimination of traffic accident hot spots caused by insufficient surface water drainage. With its help, an optimization of pavement surface drainage – under safety and economic aspects – is feasible. For the elimination of existing safety weak spots an automated ex post correction can be accomplished. For this purpose, drains (in between lanes or across travel lanes or transverse), grooves (both along and across) and special pavements like porous asphalt can be applied on any road geometry (particularly transition curves respectively sag vertical curves or a combination between them). In adaptive scenarios each element and alignment option is automatically evaluated by the program as long as an optimized constellation is found. As a result of a number of model passes, a list of recommendations for the optimized use of drainage elements and geometric design elements was given.

Computer Simulation of Hydroplaning Effects on Geometric Design - Optimization Strategies for Road Sections with Critical Rainwater Drainage

The vehicle handling is heavily influenced by the pavement condition. Even if road safety is given on a dry roadbed, by rainfall effects this is likely to be changing fast. Tire grip decreases and in case of higher water film thickness, complete aquaplaning of the vehicle can occur. The intent of this study was to analyse the impact that different influencing variables have on road safety. The factors can be subdivided in such which are based on *geometric design* (which finally has an effect on drainage path lengths), those based on the *pavement surface* (mainly macro texture, but also grooving), those based on *weather conditions* (rainfall, wind) and last those based on *vehicle conditions* (speed, tire properties, axle loads).

The range of actions for highway engineers is wide: extension of the macro texture through open-graded asphalt or grooving, setting up a speed limit (in cases of wetness), installation of drainage appurtenances (slotted drains and also grooving) or modifying the roadway alignment.

For all of the measures listed above, a computer model, called Planus, was developed. It is intended to be used by highway engineers to take the different measures under examination and compare them with each other. Also an optimization routine, e.g. for slotted drains is implemented.

Impact of geometric design properties on drainage path lengths.

Einfluss der Fahrbahnoberflächengeometrie auf die Falllinien-Längen

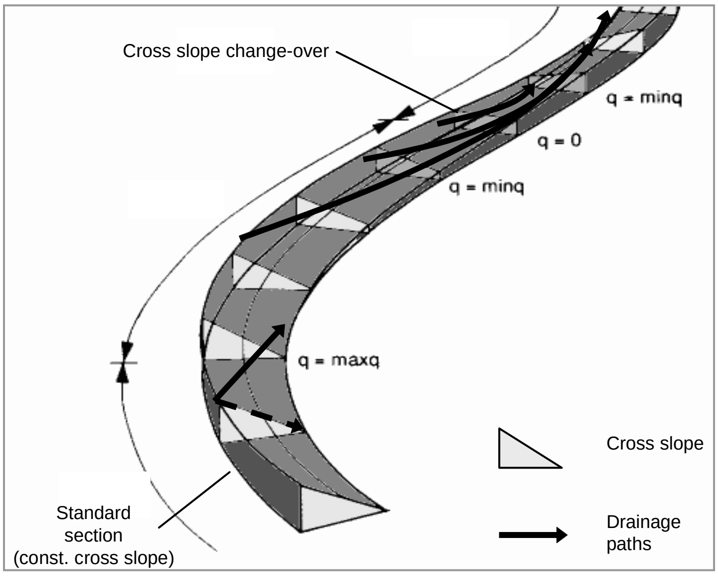


Figure 1: Impact of geometric design properties on drainage path lengths

THEORETICAL BASIS OF MODEL

The model has a multi-phase consecutive configuration. First, pavement surface topography is discretized into a mesh system. Input data are either roadway design parameters (new design) or road surface data obtained by a laser scanning device (ex post-verification of existing roads). On this surface topography, drainage paths of the runoff water are generated. Drainage paths are gradually generated by the one simple build-up rule, always to follow the path of the largest slopes. On each single drainage path, water film thicknesses are calculated by finite elements method. The next consequential step is to disperse the one-dimensional results on single drainage paths to a two-dimensional face. Thus, a specific water film thickness value is allocated to each mesh point. With these values, point for point, a specific hydroplaning speed is computed.

With the information for each point (gradient height, water film thickness, hydroplaning speed), all essential hydroplaning performance analyses of the given surface topography can be made. Additionally, drainage appurtenances can be tested.

Discretization of the pavement surface topography

The main idea of the research project was to provide methods of resolution for any kind of pavement surface topography (e.g. cross slope change-over combined with sag vertical curve) and any kind of drainage appurtenances (e.g. slotted drains in different positions and off-axis angles or slotted drains combined with grooving). Former research subjects on these purposes, which all applied analytical methods, were all faced with various problems on that account. So the approach chosen here was to discretize the pavement surface topography. In this connection, the positive side effect was that the model has also been able to superpose irregular topography characteristics, such as unevenness, singular depressions or lane grooves to the calculated surface.

The discretization routine is applied with the common parameters for the vertical and horizontal alignment of roadways. From this, it generates a mesh model of the surface.

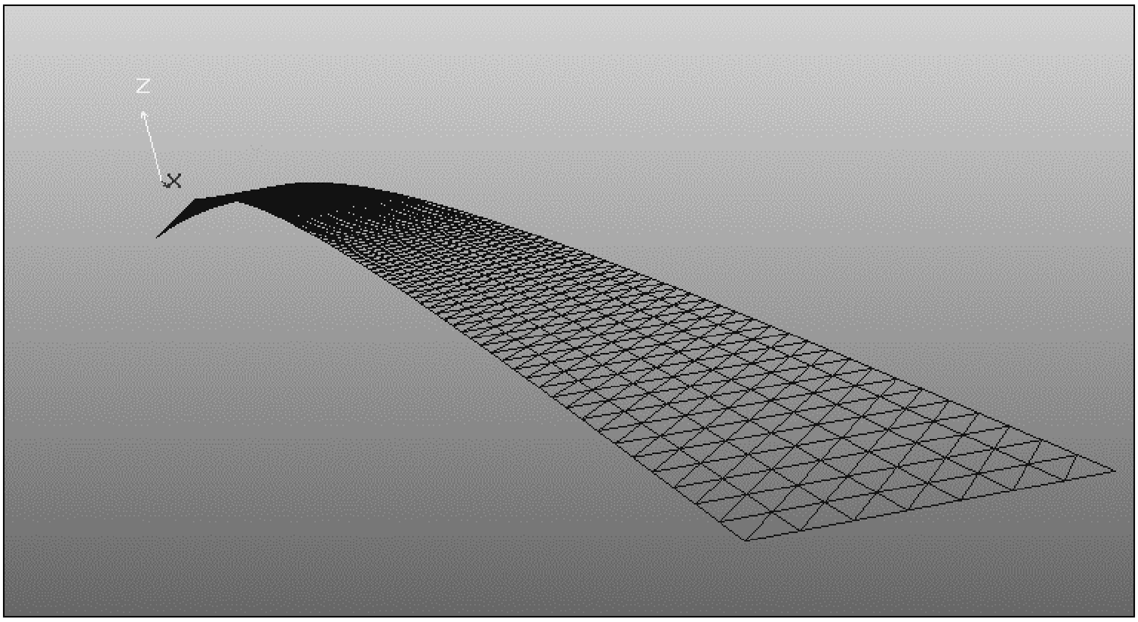


Figure 2: Three-dimensional view to the mesh model of a cross-slope change-over

The rough model mess can be set up arbitrarily. It is only limited by the working memory of the used computer. About 10-20 cm turned out to be a practicable size for good results of the researches. For example, a 13.5 m width and 200 m long roadway section would then be dissolved on a scale of 13.500 to 27.000 mesh points.

Drainage path routing

The model is based on the principles of conservation of mass and conservation of momentum. It uses a one-dimensional, steady-state form of the set of equations. Anyhow real pavement surfaces have two-dimensional shape, this assumption has two prime advantages: a) simulations run absolutely stable whereas two-dimensional attempts were to no avail as the process had broken down (Huebner, 1990), b) only one-dimensional flow can correctly be validated in runoff experiments, which was a main concern of the research project.

For computing the pavement runoff in a one-dimensional mode, single drainage paths on the pavement surface have to be generated. A flow path is defined as the course of a substantial liquid particle, which is placed somewhere on a surface and continues along the largest slope until it leaves the surface system (normally at the pavement border or through a drainage appurtenance). In fluid kinematics, this approach is called the Lagrangian approach (according to mathematician Joseph Louis de Lagrange).

As for the directions of the mass transport (fluid particles along flow paths), the slope is also responsible for the flow velocities.

Therefore the first step for the computation is the generation of flow paths for the modelling area. Even though the rules of generation are simple, the results look more complex:

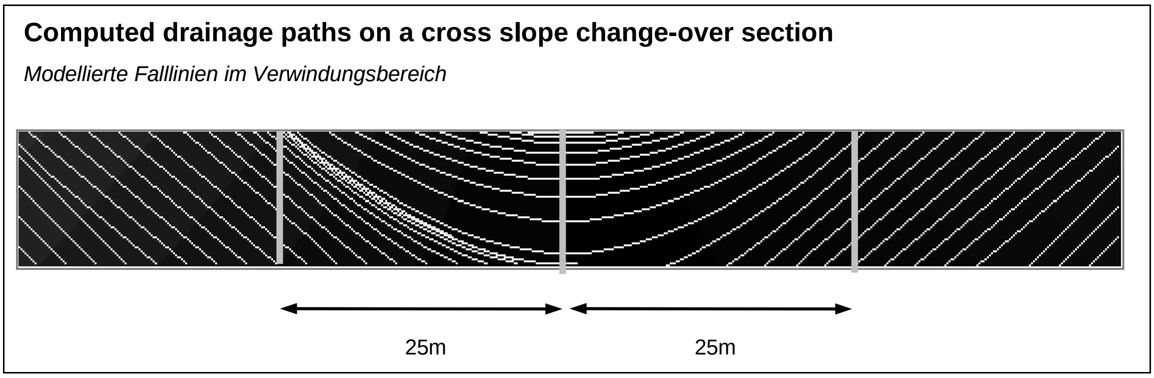


Figure 3: Computed drainage paths on a cross slope change-over section

Water film thickness calculation

The equations of conservation of mass and conservation of momentum can be reduced to steady-state flow conditions. These represent a time-constant state of maximum discharge (worst-case snapshot of the hydrologic system). Along each drainage path, water film thicknesses have then been calculated. As the pavement surface topography is available in discrete elements, the computed drainage paths are also, as shown in Figure 4:

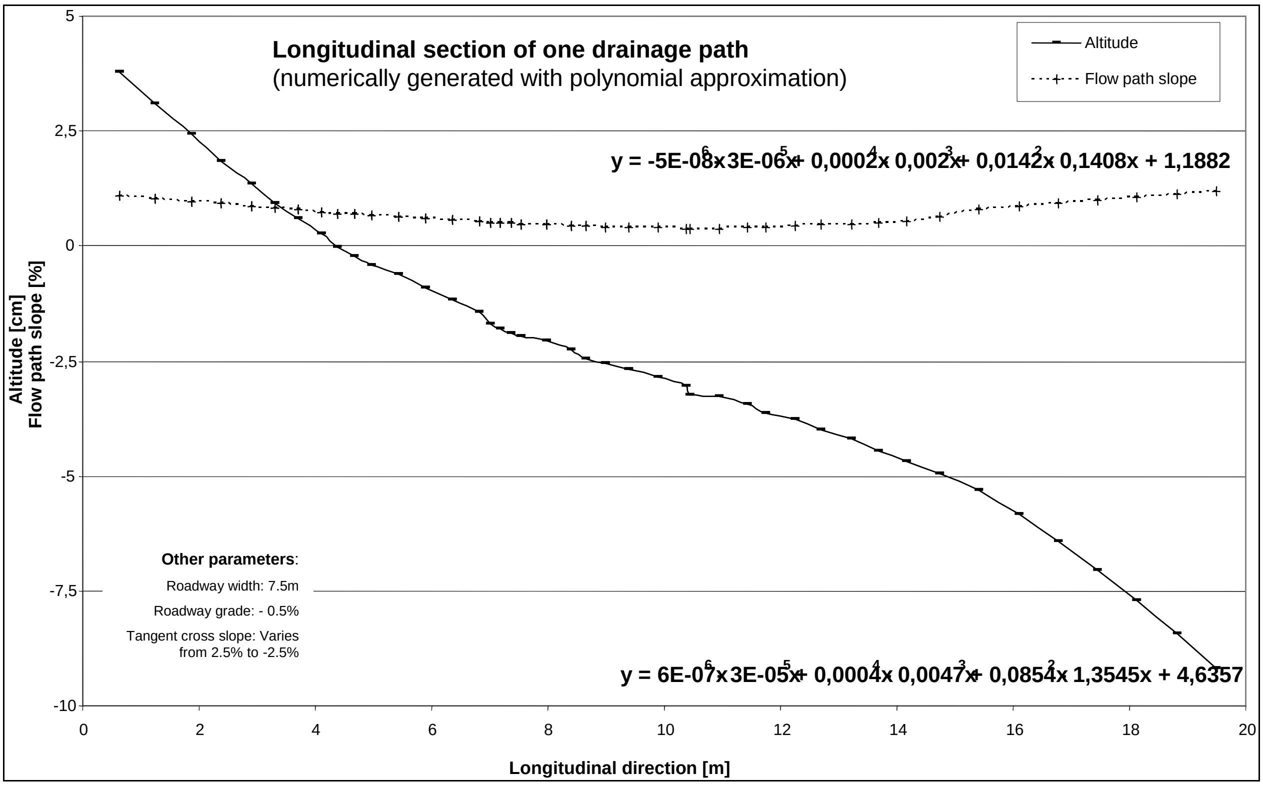


Figure 4: Longitudinal section of one drainage path

To solve the problem of the generally non-parallel drainage paths, and consequentially non-constant distances in between, a notional channel width is adopted. The channel is notional, which means that no physical border is existent. The (virtual) border is formed by its adjacent drainage paths. This helps to include the fact that, for example in the case of convergent drainage paths, as illustrated in Figure 5, the running off water masses have to be allocated in a narrowing area (respectively width). Thus, water level is increasing and flow velocity is, proportionately, also increasing.

As real two-dimensional schemes are not stable up to now for such low water levels according to sole roughness, this is a practicable method to bring multiple single one-dimensional simulations in line with a two-dimensional surface area. A little downside is that in areas, where adjacent notional channels come across, water film depths are discontinuous. Since those areas are in the middle of two drainage paths, the variance can be adjusted by the spreading algorithm.

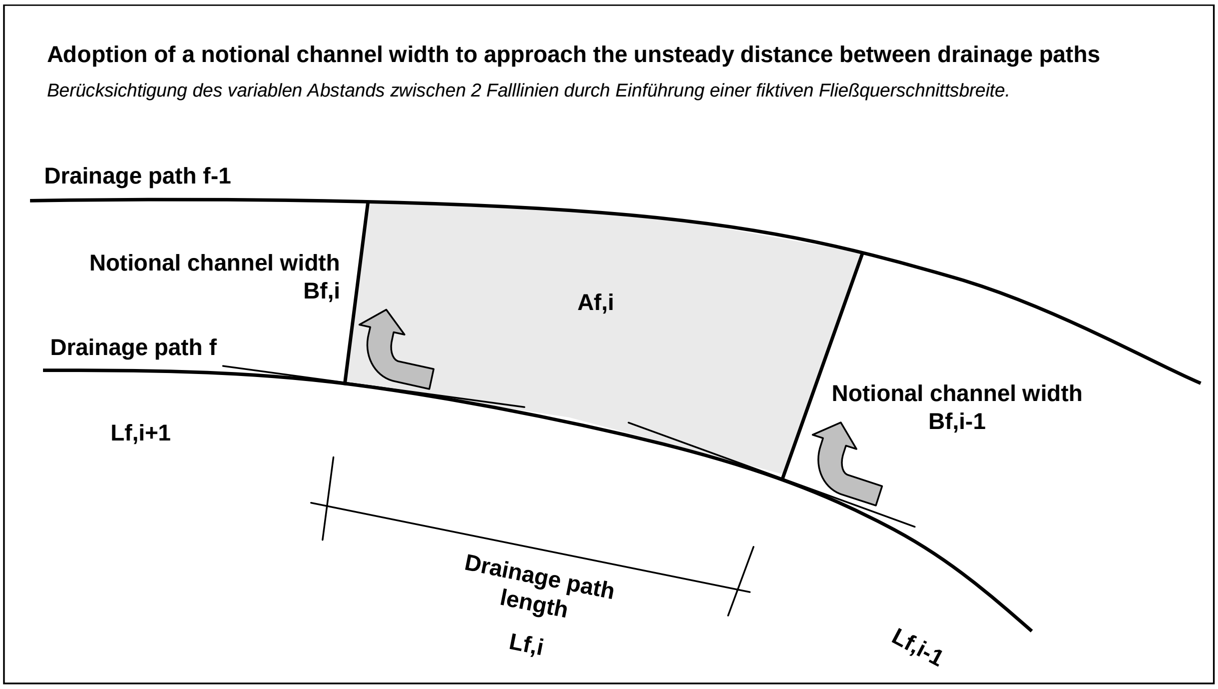


Figure 5: Adoption of a notional channel width to approach the unsteady distance between drainage paths

In the next step, the water film thicknesses have to be spread over the whole modelling area. An interpolation scheme is applied to generate a complete two-dimensional water film thickness distribution. The scheme is according to schemes for calculating the spread of concentrations on an area out of single, fixed points. The scheme is furthermore modified for not to misweight the influences of the different influencing drainage paths. An example plane computed water film thickness distribution is given in Figure 6:

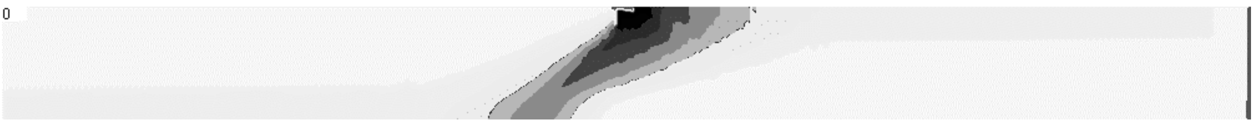


Figure 6: Water film thickness distribution over a modelling area (dark colors indicate high, light colors low water films)

PAVEMENT SURFACE RUNOFF EXPERIMENTS

Experiment setup

Objective of accomplished runoff experiments was to gain information about the distribution of water film thicknesses on real pavement surface types, which are most common on German autobahns and federal roads. The following pavement types were tested (parenthesized the corresponding, measured mean texture depth values[1]):

[1] Measured by the sand patch method, according to Kaufmann

- Portland cement concrete, surface textured by jute drapery (MTD = 0.41 mm) ,
- Portland cement concrete, surface textured by synthetic turf (MTD = 0.84 mm),
- Stone matrix asphalt 0/11, sprinkled with crushed stone 2/5 (MTD = 0.98 mm),
- Stone matrix asphalt 0/8, sprinkled with crushed stone 1/3 (MTD = 0.88 mm),
- Mastic asphalt 0/8, sprinkled with crushed stone 1/3 (MTD = 1.83 mm).

The pavements were produced with great care under laboratory conditions. Therefore a very good approximation to an ideal plane was achieved. This was a stringent requirement to get proper one-dimensional flow conditions. As mentioned above, no combination out of cross slope and gradient slope were simulated (which would mean two-dimensional flow), but only one slope, which can be considered as the slope in the longitudinal section of one drainage path (cp. Figure 4). The dimensions of the test area were chosen to 1.00m x 2.50 m. A width of 1.00 m was necessary for not to have boundary interferences, the runoff length of 2.50 m was required to note rising water film thicknesses. To simulate conditions with higher drainage path lengths than 2.50 m, border inflow rates can correspondingly be increased. So any flow path lengths are provided.

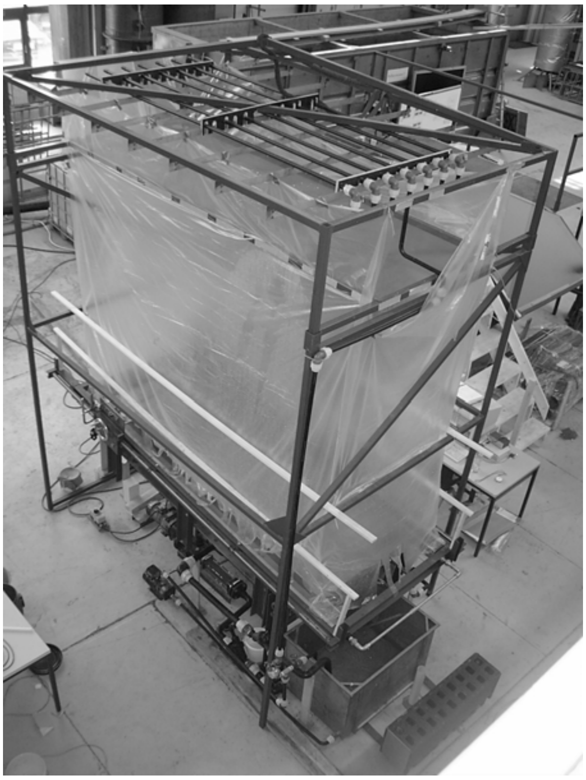


Figure 7: Left: Top view to the experimental rig. Right: Interior view of the experimental rig under sprinkling. In the front the ultrasonic-measuring device.

The experimental rig is designed to set up different gradient slopes. Inflow from the upper edge of the testing field can be varied, as well as vertical inflow through sprinkling. The sprinkling devices were attached at a height of about 3 m, so that natural rainfall conditions could be simulated best. Also the sprinkling device itself was substantially pretested to deliver rain drop sizes and charge rates matching to original conditions.

Measuring device

As measurement device, an ultrasonic sensor was used. It generates a set of 50 single metered values per second, which are averaged over a single point metered value. On the test area, 27 measuring points were established for 3 longitudinal sections, each with 9 equidistant points. Altogether, 3 one-dimensional flow paths could be analyzed. Again, the results of them were averaged over a representative flow path line.

APPLICATION AND FINDINGS

Findings of the Runoff Experiments

Clear connections between the independent variable water film thickness and its influencing variables slope, flow path length, rainfall intensity and inflow could be found and quantified. Figure 8, for example, shows the interrelation between water film thicknesses and flow path lengths. Flow path lengths of 150 m can actually be found in real situations, but not 300m: this marks out a theoretically value. As can be seen, the curves increase in a diminished scale. The set of curves displays the influence of the flow path slopes. On low slopes, water film thicknesses have high values; on high slopes, water film thicknesses are comparatively low. This can easily derived from the fact, that on low slopes, the flow velocities are also slow. Therefore less water mass can be moved on in the same time and more mass concentrates on the spot. An increasing of water film thicknesses against flow path lengths can be explained by mass input into the system (through rainfall infiltration). While rainfall infiltration rates are constant during the flow path length, the increase is diminished (non-linear) because of considerable increase of water depths in relation to texture depths, and therefore decline of flow resistance.

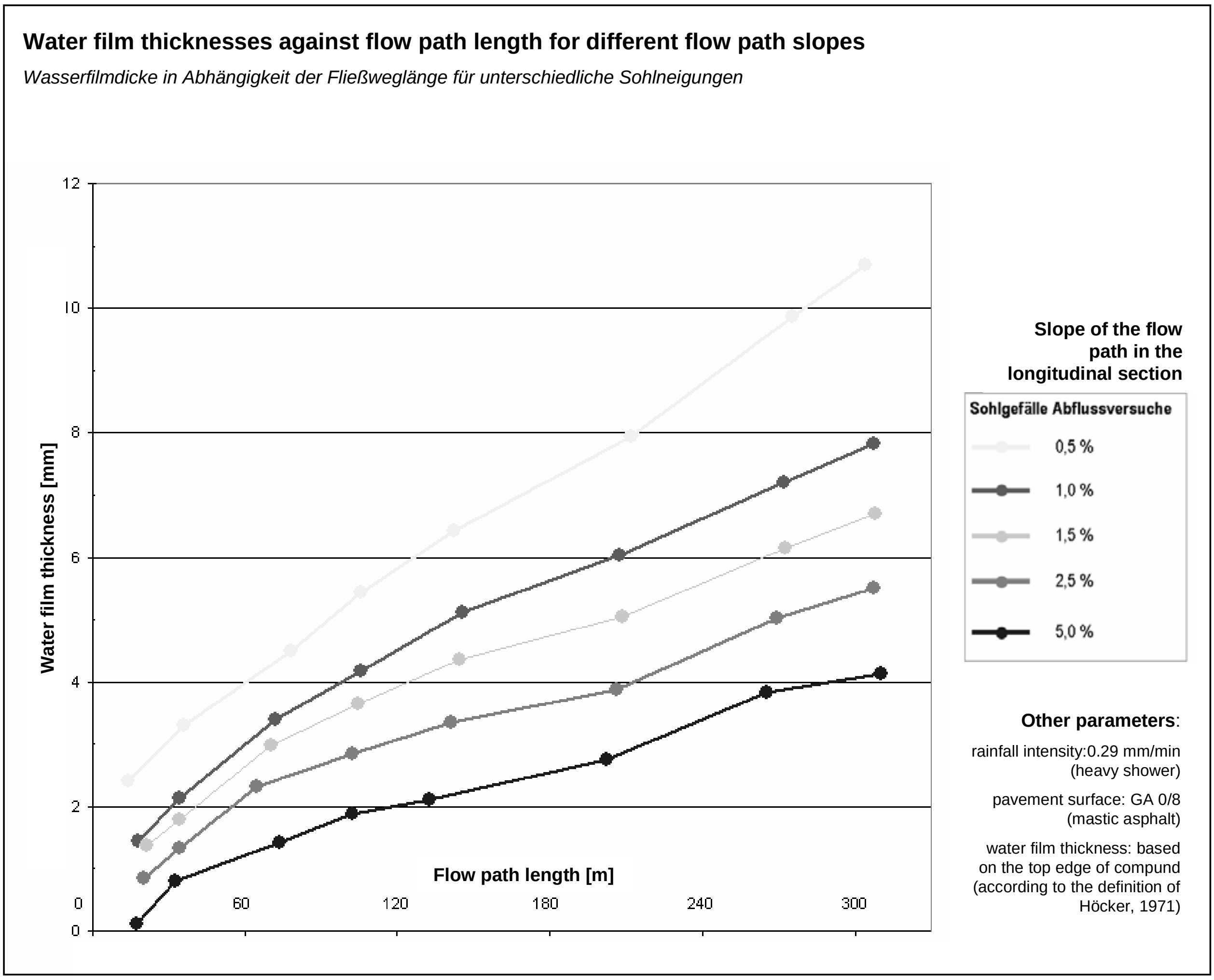


Figure 8: Water film thicknesses against flow path lengths for different flow path slopes

The above exemplified considerations and quantifications were made for all other possible variations. As a result, a set of empirical flow equations was obtained (one for each pavement type), such as results for the equivalent sand grain roughness k_S for each pavement type. With the latter, the flow resistance coefficient λ can be calculated, which is basic for the numerical simulation of water film thicknesses.

Review of roadway design parameters in cross slope change-over sections

By the application of the model, limit values, given by the German design guidelines RAS-L 1995, were reviewed regarding hydroplaning aspects. The limit value for the minimum cross slope (min q = 2.5%) in cross slope change-over sections could be confirmed. Lower values of min q (< 2.5%) would generate higher water film thicknesses, whereas higher values (min q > 2.5%) caused no fall off of water film thicknesses.

The length of the central change-over section (50 m length in general) was also reviewed. It could also be confirmed, because on higher values (> 50 m), no significant fall off of water film thicknesses occurred, on lower values (< 50m), the computed water film thicknesses raised rapidly.

The impact of roadway width to water film depths is linear (wider roadways cause higher water film thickness values), but there is logically no scope.

Only in one point, a revision of a guidelines’ limit value has to be considered: the variation of roadway grade showed that with slopes less than 2.0%, water film thickness increased. With increasing gradient slopes (above 5%) water film thicknesses also increased, but not significantly. Guidelines allow a minimum gradient slope of 0.7% in change-over sections (whereas a suggested/prefered minimum value is 1.0%). In consideration of the modelling results, a future minimum value of 1.5% (better 2.0%) can be approved.

The following figure 9 shows the impact of different roadway grades on water film thicknesses. With G = 0.0 %, high water film thicknesses occur only in a narrow range by the change-over point. As G increases, the high water film thickness area is dispersed in direction of downward slope. Simultaneously, the peak values (> about 2.5 mm) disappear. But the area of relatively high water film thicknesses (> about 1.3 mm) remains and its influence length increase (as identification for the time of exposure for a vehicle to high water film thicknesses).

The position of the in each case (of G) highest water film thicknesses, broken down by lanes, is moving to the left side. More ore less surprisingly is the fact, that the peak values, e.g. at G=6.0 %, do not occur at the centre change-over point.

Water film thicknesses on a 3-lane roadway section (13.5m width) with cross slope change-over. Variation of roadway grade (G).

Wasserfilmdicken auf einer 3-streifigen Richtungsfahrbahn (RQ 33) mit Querneigungwechsel. Variation der Fahrbahnlängsneigung (G).

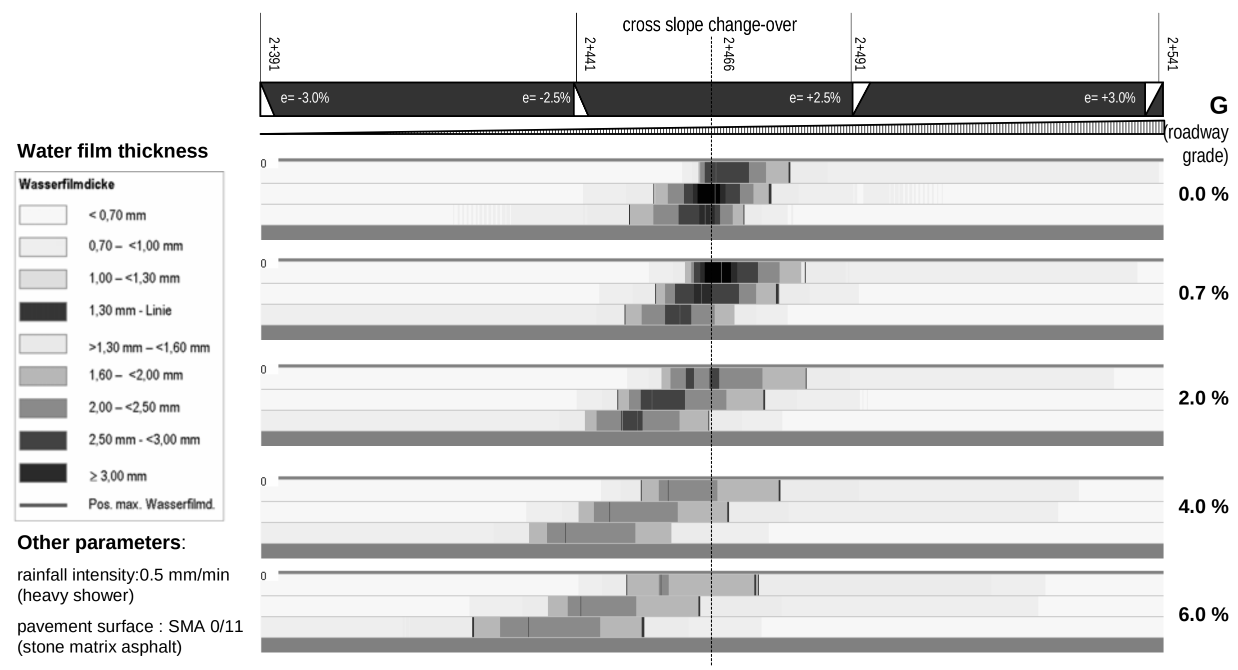


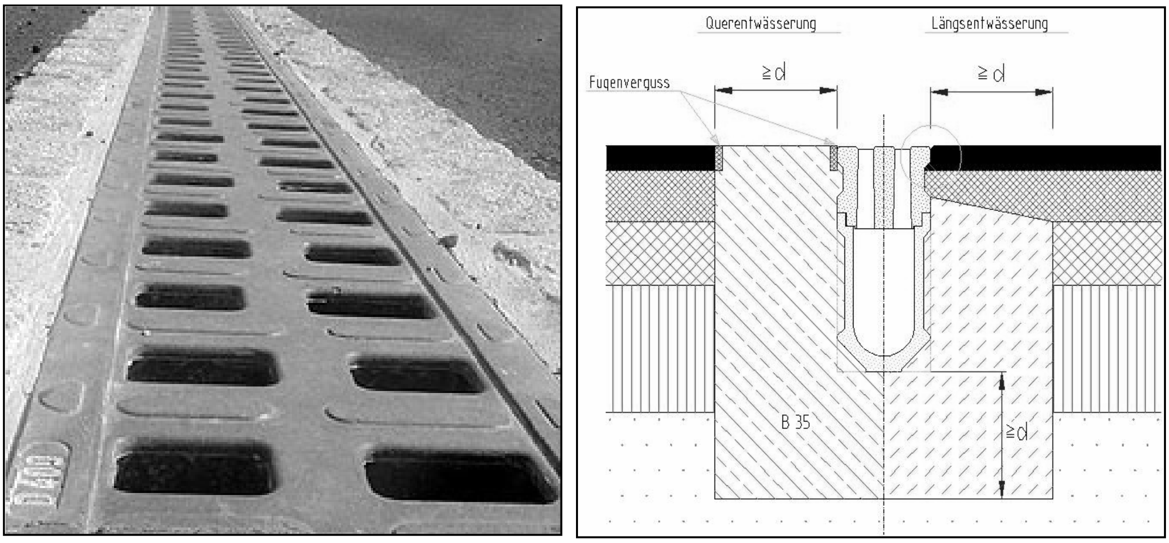
Figure 9: Water film thicknesses on a 3-lane roadway section (13.5m width) with cross slope change-over. Variation of roadway grade (G).

Analysis of Appurtenances

The optimization of design parameters is one thing; the installation of appurtenances is the other. At the design process of new roads, an optimization of design parameters is recommended. Appurtenances should only be considered, if there isn't any other possibility. On existing roadways, though, only the latter is economically useful. So both measures have their significance.
As appurtenances, there are available:

- slotted drains for the installation in roadway transversal, longitudinal (in between lanes) or across to the direction of travel
- grooving
- open graded asphalt combined with drainage appurtenances to provide internal drainage in asphalt

For slotted drains, an optimization routine was added to the computer program as a couple of Germany's federal states see slotted drains as a feasible way to eliminate traffic accident hot spots caused by hydroplaning. In figure 10, a typical slotted drain can be seen. Slotted drains used in traffic lanes are specially made for this purpose. They are monolithic and made of polymeric concrete. On the right side, a installation scheme is shown. The concrete blocks' size is about 1.5 x 1.5 m.



Manufacturer: ACO drain passavant, Rendsburg, Germany

Figure 10: Example of a slotted drain for the installation in roadways transversal to the direction of travel

First simulations with slotted drains have been completed. Figure 11 shows one of the results. For a given roadway section, in this case a cross slope change-over section, the hydroplaning speeds were computed with and without drains. The showed optimized positions of the three drains are found after several optimization passes.

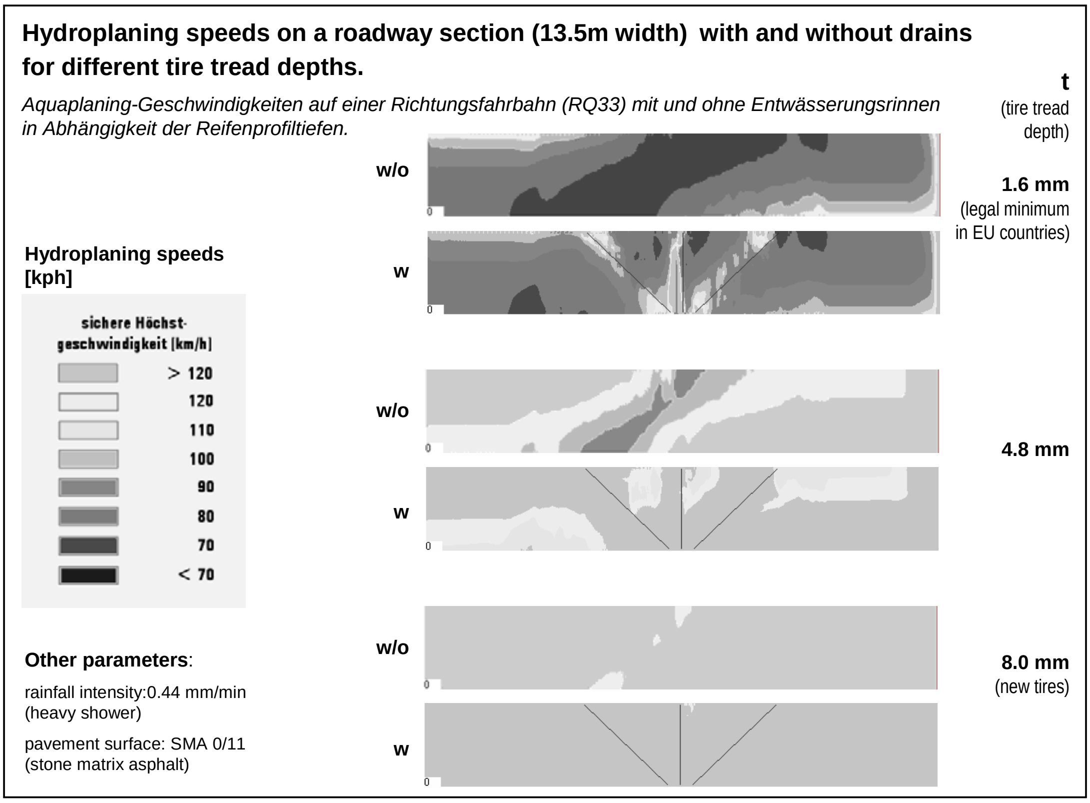


Figure 11: Hydroplaning speeds on a roadway section (13.5m width) with and without drains for different tire tread depths.

SUMMARY AND CONCLUSIONS

The developed computer program Planus can be used by highway engineers to detect potential weak points due to hydroplaning. It can be used as a tool which assists the designer considering hydroplaning aspects during the designing process. Just as well it is a useful tool to revise existing roadway sections and to take the appropriate steps to reduce the likelihood of hydroplaning.

ENDNOTES

Although the original research assignment is almost finished, the research activities at that subject are not closed yet. At that time, a converting routine for laser scan data of real pavement surface topographies is developed. The scans were taken at cross scope change-over sections at the autobahn A8 nearby Stuttgart. These sections are at the same time major accident hot spots in cause of hydroplaning.

In addition, the basis theories for adding a grooving module to the computer program are in the developing process.

The program has been used up to now mainly for validating reasons and for basic tasks. A number of further analyses of hydroplaning concerns can be accomplished with this tool.

REFERENCES

ACO DRAIN PASSAVANT GMBH (2002): www.acodrain.de, Rendsburg, Germany

FORSCHUNGSGESELLSCHAFT FUER STRASSEN- UND VERKEHRSWESEN (FGSV) (1995): „Richtlinien fuer die Anlage von Strassen – Teil: Linienfuehrung (RAS-L)“, Ausgabe 1995, Koeln, Germany.

HOECKER, H.J. (1971): „Die Oberflaechenentwaesserung von Fahrbahnen und ihre Bedeutung fuer den Strassenentwurf“. Forschung Strassenbau und Strassenverkehrstechnik, Heft 118, Herausgegeben vom Bundesminister fuer Verkehr, Abteilung Strassenbau, Bonn, Germany.

HUEBNER, R.S. (1990): „Overland Flow on Highway Pavements: Comparison of a One-Dimensional Kinematic Model and a Two-Dimensional Finite Element Model”. Ph.D. Dissertation, Pennsylvania State University, Pennsylvania, USA.

KAUFMANN, N. (1971): “Das Sandflaechenverfahren”, *Strassenbau-Technik*, 3, 71