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Preventing aquaplaning phenomenon through technical solutions

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Professional paper

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Preventing aquaplaning phenomenon through technical solutions

The aquaplaning of a road vehicle occurs when a layer of water appears between the wheels of the vehicle and the road surface. The aquaplaning causes loss of wheel adherence, and results in a reduced vehicle control capability. The efficiency of technical solutions applied on standard roads is analysed using a dedicated computer software called the Pavement Surface Runoff Model. The paper places emphasis on the significance of constructing a good quality pavement-structure wearing course, its influence on traffic safety, and the correlation between geometric properties of road elements and the aquaplaning phenomenon.

Key words:

aquaplaning, road safety, water film, pavement surface, road geometry design

Stručni rad

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Prevenција pojave akvaplaninga primjenom tehničkih mjera

Do pojave akvaplaninga, kod cestovnih vozila, dolazi kada se između pneumatika vozila i površine kolnika pojavi sloj vode. Akvaplaning uzrokuje gubitak prionjivosti pneumatika što za posljedicu ima smanjenu upravljivost vozilom. Učinkovitost tehničkih rješenja koja se primjenjuju na uobičajenim cestama analizirana je pomoću specijaliziranog računalnog programa Pavement Surface Runoff Model. U radu je pokazana važnost kvalitete izvedbe habajućeg sloja kolničke konstrukcije, njen utjecaj na sigurnost odvijanja prometa te korelacija između geometrijskih karakteristika elemenata ceste i pojave akvaplaninga.

Ključne riječi:

akvaplaning, sigurnost cestovnog prometa, vodni film, površina kolnika, geometrijsko oblikovanje ceste

Fachbericht

Alina Burlacu, Carmen Răcănel, Adrian Burlacu

Vermeidung von Aquaplaning durch Anwendung technischer Maßnahmen

Zum Auftreten von Aquaplaning bei Straßenfahrzeugen kommt es, wenn sich zwischen dem Fahrzeugreifen und der Fahrbahnoberfläche eine Wasserschicht bildet. Aquaplaning verursacht einen Verlust der Reifenhaftung, was eine Verringerung der Lenkbarkeit des Fahrzeugs zur Folge hat. Die Wirksamkeit technischer Lösungen, welche auf üblichen Straßen angewendet werden, wurde mithilfe des speziellen Computerprogramms Pavement Surface Runoff Model analysiert. In der Abhandlung wird die Bedeutung der Qualität der ausgeführten Verschleißschicht der Fahrbahnkonstruktion, deren Einfluss auf die Sicherheit des Verkehrsflusses sowie die Korrelation zwischen den geometrischen Merkmalen der Straßenelemente und des Auftretens von Aquaplaning aufgezeigt.

Schlüsselwörter:

Aquaplaning, Sicherheit im Straßenverkehr, Wasserfilm, Fahrbahnoberfläche, geometrische Straßengestaltung

1. Introduction

Water present on roadway surface is an important element for traffic safety, as it can have an effect on the driver's visibility and can also facilitate the occurrence of aquaplaning. The latter is an especially dangerous phenomenon consisting of the tyre planing (gliding) on the water film present on the road surface. It occurs under specific conditions, when the vehicle exceeds a certain speed, and also when the shape of the tyre and the texture of the road surface do not favour rapid water drainage. In such situations, a continuous water film of variable depth appears between the tyre and the road surface. The friction coefficient is reduced to 0.1, especially when the wheels are locked by braking (Figure 1).

This accumulation of water does not affect solely the areas with smoothness deficiencies, but also those exhibiting problems with evacuation of rainwater. Furthermore, some road configurations can favour water accumulation on the carriageway, such as transition curves sectors. In a German study [1] involving a six lane highway section, the authors highlight the fact that the risk of traffic accidents occurring while it is raining is twice as high at progressive curves compared to other highway sections. For a dry carriageway, the risk is roughly the same, which shows that this aspect of infrastructure design must be further studied, and that efforts must be made to develop new methods aimed at improving the situation.

The research on aquaplaning roughly dates back to the year of 1930 [3], when it was primarily motivated by the desire to

improve the design of drainage facilities. However, it was not until the 1960s that the effect of road drainage on traffic safety was identified [4], as a result of growing road networks, wider roads, and higher vehicle speeds. The aim was to investigate the effect of slope and drainage path length on water depth. In the 1970s, the research on pavement surface runoff was first linked to the real roadway geometry in order to investigate the effect of design parameters on water depth [5].

2. Relevant factors

2.1. Weather conditions

In our country, the pluviometric data registered at weather stations for the period between 1901 and 2000 show that there is a general tendency of decline in annual precipitation, but also an escalation of the drought phenomenon in the southern part of the country after 1960. An increase in the annual frequency of days with heavy rain (the largest daily quantities were 12 %) and extremely heavy rain (the largest daily quantities were 40 %) was registered in some regions in the period between 1946 and 2000.

Torrential rains are caused by high activity of tropical humid air or maritime polar air over our country's territory, the uneven warming of the Earth's surface, and its interaction with the former during the warm season of the year.

Maximum intensity class structure distinguishes for torrential rains a predominance of the one over 1.0 mm/min (85.2 %), the situation being identical in the case of rainfall events of annual maximum intensity (Table 1). The duration of the maximum intensity, in the case of torrential rains, varies between 2 and 5 min (55.4 %), which is followed by the 1 min class (under 25.0 % in both cases). The situation is similar for the rainfall of maximum annual intensity, where the duration of the maximum intensity of up to 5 min, adds up to 95.3 % of the cases [6].

The graph given in Figure 2 shows a rainfall intensity of 1.8 mm/min, and a duration of 5 minutes for a frequency of once every two years, up to a value of almost 4 mm/min for the same 5-minute duration, for a frequency of once every 100 years [7]. According to experts [8], this precipitation not only occurs more frequently than before, but it is also more abundant, which automatically implies the need to take appropriate measures in order to improve the infrastructure and prevent the occurrence of the aquaplaning phenomenon.

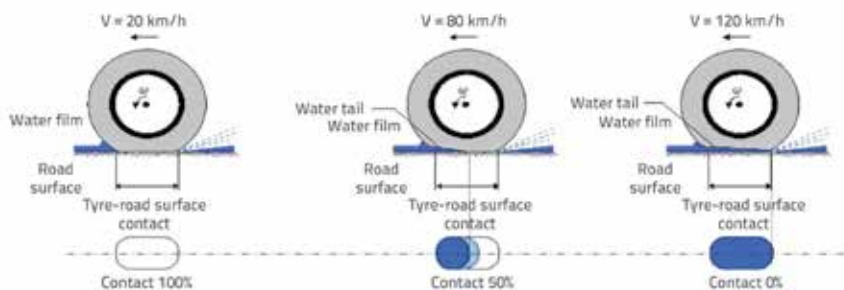


Figure 1. Model for three areas of contact between tyre and carriageway [2]

Table1. Frequency by intensity classes of torrential or annual maximum intensity rainfall, depending on their duration [%] [6]

Duration of rainfall	Torrential rain			Maximum annual intensity rainfall		
	Maximum intensity [mm/min]					
	<0.5	0.5 – 1.0	>1.0	<0.5	0.5 – 1.0	>1.0
< 1 hour	-	1.5	23.6	0.2	1.7	32.1
1-2 hours	-	1.5	18.8	-	1.2	28.6
2-3 hours	-	1.5	14.0	-	0.4	16.4
3-6 hours	0.4	9.2	27.7	-	0.4	14.3
> 6 hours	-	0.7	1.1	-	0.8	3.9
Total	0.4	14.4	85.2	0.2	4.5	95.3

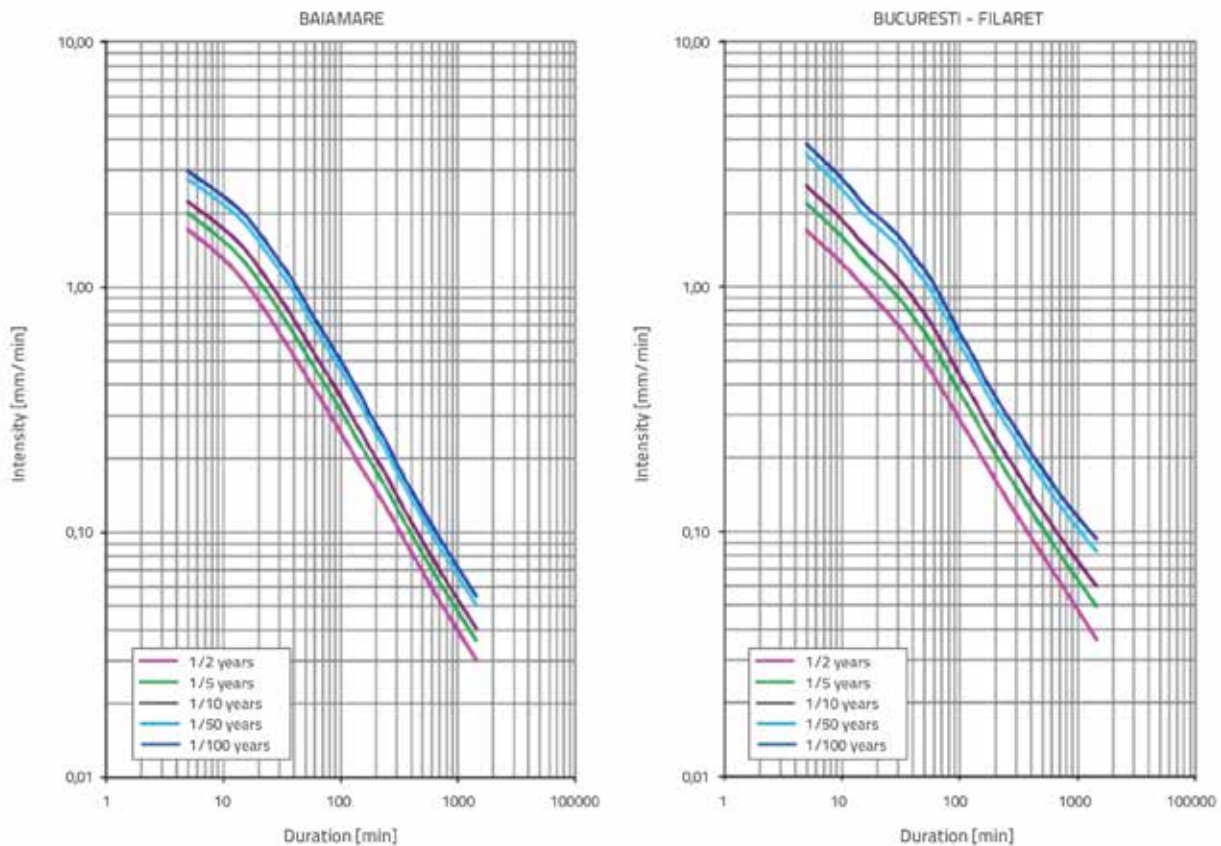


Figure 2. Intensity – duration – frequency curves based on data extracted from rainfall graphs [7]

2.2. Road geometry

Road geometry refers to a three-dimensional overlaying of the elements of the road's layout with the vertical alignment and the road's cross sections, all of them drawn in two dimensions in conformity with current standards. The way these elements interact makes the basis for assessing if the road's geometry is correct, by analysing some aspects such as road visibility, rainfall drainage capacity, and comfort of participants in traffic. In this subsection we analyse the road's capacity to drain water from its surface, from the perspective of its geometry. The slopes of the vertical alignment (min. 0.5 % and max 8.0 % [9]) and those of the cross section (min. 0.2 % and max. 7.0 % [9]) are the ones that give the direction of water drainage, drainage speed and the lengths of the drainage means.

In some cases, water drainage from the surface of the carriageway is not exactly optimal, even if the road was realised in accordance with design requirements. These cases are mostly encountered in transition areas between two consecutive transition curves, as mentioned in the study from Germany [1], and favour the occurrence of the aquaplaning phenomenon, especially on roads that allow high traffic speeds and have a considerable carriageway width.

Particular elements of these transition areas are transition curves (in the road layout) and superelevation (in the cross section). Figure 3 is the three-dimensional representation of such a road section, composed of two consecutive connections

of type: circular arc – clothoid, with constant radii R_1 and R_2 , respectively. According to our country's standards, the usage of transition curves is mandatory.

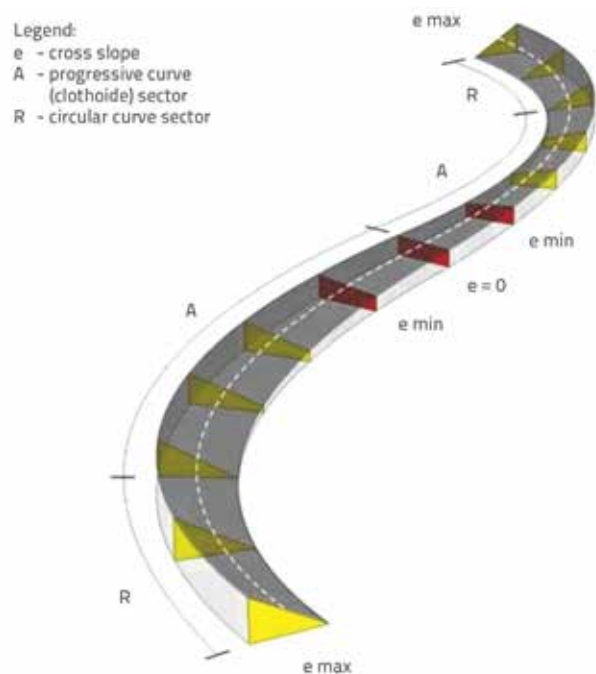


Figure 3. Three-dimensional representation of two consecutive opposite transition curves [10]

What affects the drainage capacity of this road section is not the curvature change but the change in elevation slope, especially as the passing through a null cross section is necessary, as specified in prevailing standards. This fact can also be observed in Figure 4, where the water drainage directions are represented for two cases: constant cross and longitudinal slopes, but also for the case under study, where we have a transition cross section, taking into consideration a constant longitudinal slope. Because of direction change, the length of the tracks that represents water drainage in transition sector is greater. Moreover, the water drainage slope decreases with the reduction of the cross section slope, which implies heavier drainage, resulting in accumulation of water on the carriageway.

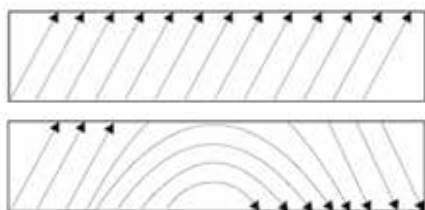


Figure 4. Water drainage direction for cross section with a constant slope (up) and for a transition cross section (down), both with a constant longitudinal slope

To ensure a better drainage of rainwater from the carriageway, the central area of transition sector must be treated with great attention, especially due to the fact that cross slopes have values under the necessary minimum ones. Thus, this area is designed in strict conformance with current standards (Figure 5).

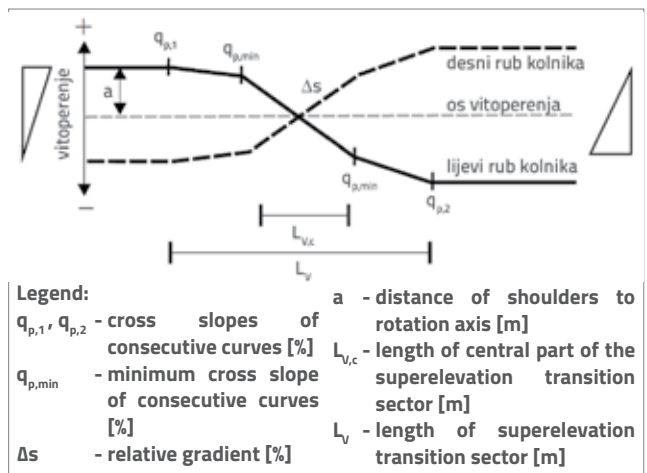


Figure 5. Projecting elevations in opposite consecutive curves [10]

Because of the changes that occur due to elevation, the shoulders of the carriageway are inclined from the longitudinal slope by Δs (with values between 0.1a and 0.9 %) [10]:

$$\Delta s = \frac{q_{p,1} - q_{p,2}}{L_{v,c}} a \tag{1}$$

In some cases, water drainage problems may occur even if all relevant standard requirements are respected, and efforts must be made to find complementary solutions.

2.3. Roadway surface

Roadway texture is a parameter that influences in multiple ways the safety and comfort of participants in traffic (by noise, resistance, roughness, skidding) and can be defined as the deviation of the real surface texture from a smooth surface in a given wavelength of λt. On the basis of this principle, four texture categories have been defined [11]:

- Micro texture: λt < 0.5 mm;
- Macro texture: 0.5 mm < λt < 50 mm;
- Mega texture: 50 mm < λt < 500 mm;
- Unevenness: 500 mm < λt.

The micro texture affects mainly the asperity, as demonstrated by many laboratory studies. The research made on macro texture, which is responsible for adequate water drainage from the carriageway, is presented in this subsection. The mega texture and unevenness also influence water drainage through longitudinal slopes. Nevertheless, they will not be considered in this study.

A characteristic element of the carriageway surface macro texture is a retention volume depending on texture depth. When this volume is insufficient for rain water volume, a continuous water film will form on the carriageway. At the same time, because of the asperity of the texture, a resistance to drainage is created, which can cause slow discharge and formation of areas with a larger depth of water film (Figure 6).

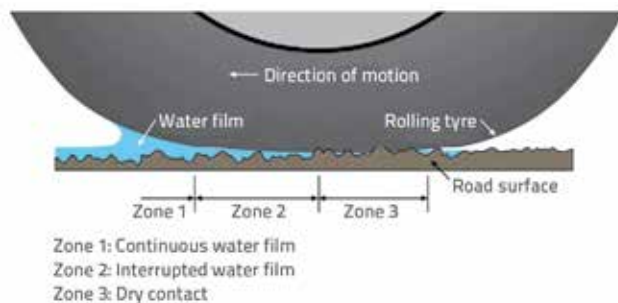


Figure 6. Water film on roadway surface at the contact between tyre and carriageway [12]

3. Analysis by pavement surface runoff model software

The water flow that discharges from the carriageway during and after a rain episode is an unstable and time dependant process. Figure 7 shows the profile of water drainage from the carriageway as related to time, and involving three stages: moistening, stable flow, and drying. If the roadway surface has asperities, the moistening and drying processes are further divided into two stages, as follows:

- t0 < t < t1 water starts to occupy the available retention volume, V1;

- $t_1 < t < t_2$ water volume exceeds the retention volume and starts forming a water film on the carriageway, until reaching a constant level;
- $t_2 < t < t_3$ water volume forming the film is defined as moving volume ($V_2 - V_1$) and is constant;
- $t_3 < t < t_4$ water volume starts to decrease at t_3 , the moment the rain stops, steadily diminishing the depth of the water slip;
- $t_4 < t$ water film disappears completely and only the water from the retention volume remains, which gradually evaporates.

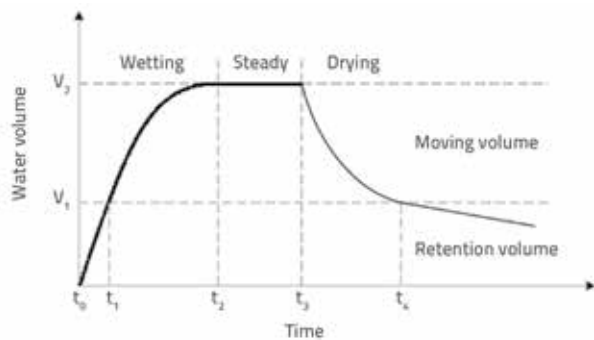


Figure 7. Graph showing drainage of water from pavement over time [10]

Concerning aquaplaning, the second stage, i.e. constant flow, is the most dangerous period, because the depth of the water film is at its maximum. The Pavement Surface Runoff Model (PSRM) software developed by Stuttgart University allows complete simulation of the way in which water drains from the carriageway, depending on road geometry details, different types of roadway surfacing, different amenities for taking in used water, as the intensity and duration of rain episodes may vary.



Figure 8. Window for defining geometric elements (PSRM software)

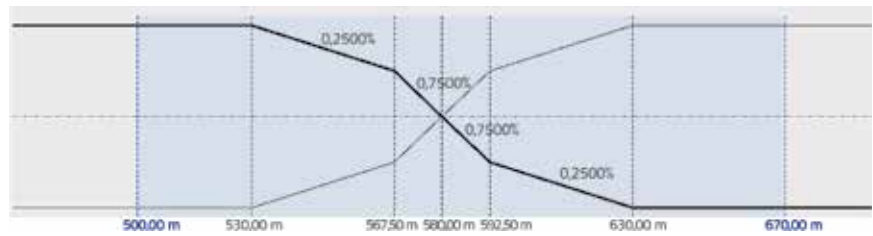


Figure 9. View of road profile analysed using PSRM software

The PSRM software was used to analyse several types of road and highway sectors, composed of two consecutive opposite curves which, when the slope changes, pass through the zero cross section (null profile), the objective being to mark out the problems concerning rain water drainage from the carriageway. At the same time, in conformity with the earlier mentioned standards, the carriageway width, the conversion-broadening length, the vertical alignment slope, the elevation slope, and the type of roadway surfacing, were introduced as variables and entered in the window presented in Figure 8, with a preview in Figure 9. Moreover, the rain intensity of 1.5 mm/min for 5 minutes was chosen for simulation purposes, in accordance with diagrams from the National Standard no. 9470-73. This is characteristic value for annual repeatability of this event in some areas of the country (Figure 10).



Figure 10. Window for entering precipitation characteristics (PSRM software)

The most unfavourable cases were taken into consideration and analysed:

- 18 hypotheses for roads, for a carriageway width of 14 meters, the conversion-elevation length of 45 m and a variation of the vertical alignment slope within the values of 0.5 %, 3.5 % and 6.0 %, the elevation slope of 3 % and 6 %, the roadway surface having a fine texture (average texture height: 0.4 mm), average texture (average texture height: 0.89 mm) and very coarse texture (average texture height: 1.8 mm);
- 12 hypotheses for highways, for a carriageway width of 10 meters in one direction, the conversion length of 140 meters, 0.2-4 % variation of vertical alignment slope, elevation slope of 3 % and 7 %, and roadway surfacing varying in the same manner as in the case of roads.

After analysis of 30 above mentioned cases, the greatest water film depths were registered as shown in Figure 11 and Figure 12.

- Road: a very coarse roadway surfacing, with an elevation slope of 3 %, vertical alignment slope of 0.5 %, conversion-elevation length of 45 meters, and carriageway width of 14 meters.

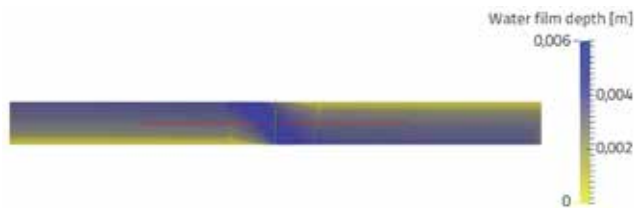


Figure 11. Water film depth on carriageway of a road sector (PSRM software)

- Highway: a very coarse roadway surfacing, with an elevation slope of 3 %, vertical alignment slope of 0.2 %, conversion-elevation length of 140 meters, and carriageway width of 10 meters in one direction.

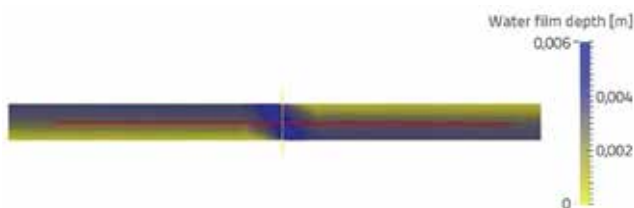


Figure 12. Water film depth on carriageway of a highway sector (PSRM software)

4. Technical solutions and recommendations for aquaplaning prevention

Although exact equation for accurate calculation of the speed at which aquaplaning occurs has yet to be developed, empirical studies have revealed the fact that the driver loses control of the steering wheel because of accumulation of water on the carriageway at a speed of at least 85 km/h, on a water film of at least 2.5 mm in depth, at a distance of more than 9 meters. A series of studies have been made in Germany on this issue over the last few years [1, 2, 10]. The focus of these studies was on the climate change and the increase in the number of traffic accidents during rain. We were able to identify three types of technical solutions proposed and used at several locations. These solutions are presented in the following subsections.



Figure 13. Examples of transverse gutters built on a highway in Germany

4.1. Transverse road gutters

In the German region of Brandenburg, in a sector of the A10 Highway south of Berlin, there is a highly dangerous road segment made of concrete, which was built in the years immediately following the unification of Germany. Even though its design took into consideration weather conditions with heavy rainfall, the proposed transverse slope was not sufficient, which resulted in a high number of road accidents due to the phenomenon of aquaplaning. The only adequate method for this section involved construction of transverse gutters, made of concrete and covered with metal bars. These gutters were built across the entire width of the carriageway, including the emergency lane in the case of highways (Figure 13). The gutters are no less than 30 cm in width and several can be assembled along a sector, at a distance of minimum 5 meters between individual gutters, as shown in simulations made with specialised software, such as the Pavement Surface Runoff Model.

As an example, the least favourable cases presented in the previous subsections were assumed, and simulations were made for 3 and 5 transverse gutters for a road sector, and 5 and 7 transverse gutters for a highway sector, as shown in the following figures (Figure 14 and Figure 15):

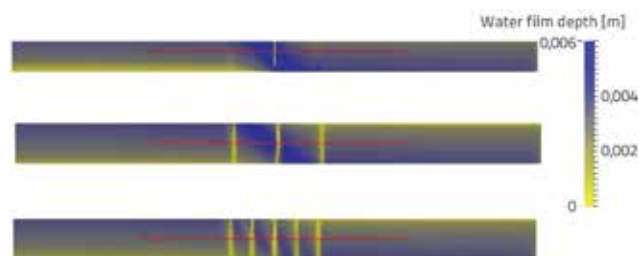


Figure 14. PSRM software simulation of the effect of transverse gutters on a road sector

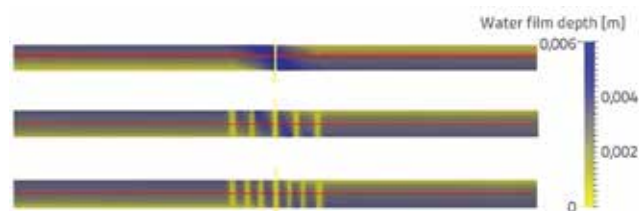


Figure 15. PSRM software simulation of the effect of transverse gutters on a highway sector

4.2. Diagonal slope

Relevant studies show that the most dangerous zone, i.e. the zone most susceptible to the risk of aquaplaning, is located in the area where the cross section meets the zero slope, in the transition zone between two successive opposite curves. To eliminate this profile, developed countries such as Germany, Austria and

Switzerland (Figure 16) use a technical solution that involves creation of a diagonal slope that does not follow upper shoulders of the converted profiles. Thus, the transverse profile of the roof type, with slopes of 2.5 %, is realized at the point where the cross section meeting the zero slope was initially found.

This method is mentioned in German standards RAS-L (FGSV 1995) and RAA (FGSV 2008), but only the latter presents the formula for calculating the length of the diagonal slope, in relation to the width of the carriageway and design speed:

$$L_v = 0,1 \cdot B \cdot V_p \quad (2)$$

where:

L_v - length of diagonal slope [m]

B - carriageway width [m]

V_p - design speed [km/h].

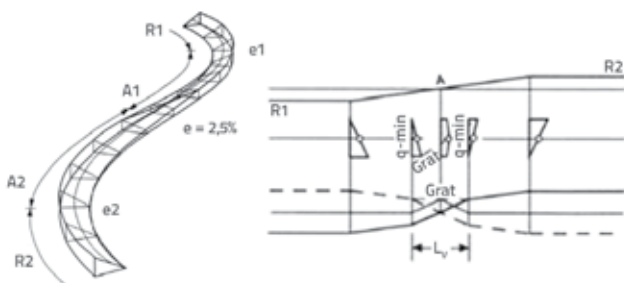


Figure 16. Example of case where diagonal slope was used [13]

The least favourable cases presented in the previous subsection were taken into consideration, and two simulations were made for the road sector and highway sector, respectively, as shown in the following figures (Figure 17, Figure 18): The main disadvantage of this technical solution is the considerable difficulty involved in actual realisation of the solution. However, the results for diminishing the depth of the water film are very good, as it can be observed in previous figures.

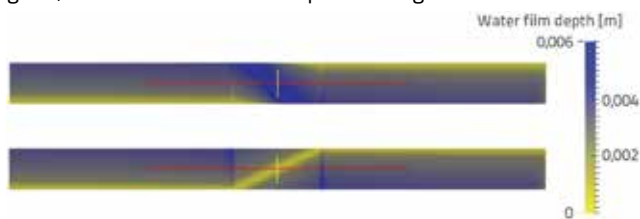


Figure 17. PSRM software simulation of the effect of diagonal slope, road sector

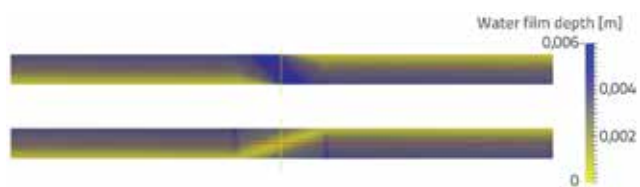


Figure 18. PSRM software simulation of the effect of diagonal slope, highway sector

4.3. Roadway surface grooving

Another measure that is used to facilitate rapid water drainage from the carriageway is to groove the road surface using a special device with diamond disks. Thus, tiny longitudinal or transverse furrows are created on the cement concrete surface of the roadway, as shown in Figure 19. Their dimensions are established using the following relation:

$$V_c = B_c \cdot T_c \cdot \frac{1000}{S_c + B_c} \quad (3)$$

where:

V_c - groove volume [mm³/m]

B_c - groove width [mm]

T_c - groove depth [mm]

S_c - distance between grooves [mm].

German standards recommend maximum groove width between 2.4 mm and 2.6 mm for longitudinal grooves, because of negative impact they can have on motorcycle traffic, and between 6 mm and 10 mm for transverse grooves. The minimum depth has yet to be determined, but the recommended value is 3 mm, while the maximum depth is around 5 mm, as an additional increase in depth would imply much higher costs.



Figure 19. Grinding grooves on roadway surface

The introduction of grooves on road surface decreases the depth of the water film considerably. However, the usefulness of such grooves is reduced during winter because of the frost-defrost phenomenon. This method can therefore be considered as a temporary measure only, and should be applied solely on cement concrete roads.

5. Conclusions

Based on the studies involving software simulation, and case studies made in Germany regarding several recently implemented technical solutions, this paper demonstrates the importance of the superior quality of roadway surfacing, and presents the way in which it can influence traffic safety, while also providing the correlation between geometric road elements and the aquaplaning phenomenon.

Concerning the studies on the occurrence of aquaplaning, it should be noted that the presence of water on the carriageway has an important role in increasing the risk of traffic accidents, which is influenced by the horizontal and vertical road works, and by characteristics of roadway surfacing.

Following more frequent occurrence of heavy rains over the past several years, and an increase in their intensity, it is estimated that this increasing trend will continue and that the quantity and intensity of precipitation will further increase in the future. The situation is additionally aggravated by alarming statistics on traffic accidents involving the loss of vehicle control during rainfall episodes. That is why current infrastructure condition must be improved by adapting road design to recent climate change.

Therefore, it is recommended to avoid cases similar to those presented in Section 3, with a very rough roadway surfacing, with an elevation slope of 3 %, and with the vertical alignment slope (grade) of 0.5 % and 0.2 % for road and highways, respectively. After running the Pavement Surface Runoff Model software, these were the least favourable cases that resulted in the creation of water film of up to 6 mm in depth, which implies a very high risk of aquaplaning.

A series of solutions to solve these problems, already implemented in certain sectors of Germany and Austria, is also presented in this paper, together with an analysis of the most unfavourable situations from the National Standard STAS 863-85, related to the weather conditions specified in STAS 9470-73.

The use of transverse road gutters results in the decrease of water film depth from 6 mm to 4 mm, and even to 2 mm, which considerably diminishes the risk of aquaplaning. The same result is also obtained by implementing diagonal slopes in order to eliminate the profile with zero slope between two consecutive opposite slopes. Good results have been achieved in practice by both methods, the only inconvenience being the difficulty in their implementation, as special machinery and qualified personnel are required.

Another measure presented in the paper involves grooving the road surface by grinding special small furrows for draining rain water both along and across the road, as necessary. In our country, this method can be considered as a short term solution because of climate conditions. Nevertheless, it can be implemented in areas with high risk of aquaplaning, as a means of monitoring behaviour of drivers and evolution of traffic events.

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