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Addressing aquaplaning challenges on wide motorway pavements: A review of pavement superelevation methods in poorly drained zones

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Abstract

The effective drainage of motorway pavements is of the utmost importance for ensuring road safety and the long-term durability of the pavement structure. Motorway sections with inadequate drainage exhibit accelerated deterioration, necessitating increased investments for rehabilitation or reconstruction. Inflection zones on motorways constructed in flat terrain are especially prone to aquaplaning (or hydroplaning). In such topographically favourable conditions, the motorway's horizontal geometry, typically comprising large circular and transition curves, is combined with shallow longitudinal grades dictated by the flat terrain. As a result, in the motorway inflection zones both cross and longitudinal grades are close to zero, thus producing poorly drained pavement surfaces with increased water film depths. This issue is exacerbated with an increase in the number of driving lanes or the overall width of the motorway cross-section. To reduce poorly drained pavement areas in motorway inflection zones, national road authorities across Europe use different measures against aquaplaning. These measures encompass the construction of porous asphalt as the pavement wearing course, increase in longitudinal grades, implementation of special superelevation methods - such as crowned pavement and variable pavement superelevation along reverse curves, occasional application of "negative" pavement cross grades in curves of extremely large radii (thus avoiding superelevation et all) and the incorporation of additional construction measures, such as transverse gutters set across the roadway. This paper primarily addresses superelevation methods that could be applied for aquaplaning risk mitigation in motorway inflection zones in light of anticipated climate changes that may impact road infrastructure across European countries.

Keywords: aquaplaning, motorway drainage, water film depth, pavement superelevation, inflection zone, climate changes.

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1. Introduction

According to US Federal Highway Administration, up to 70% of weather-related traffic accidents happen on wet pavement or in inclement weather. Consequently, providing efficient pavement surface drainage represents one of the most challenging road safety problems.

Because of high aquaplaning potential, stormwater drainage on superelevation transition sections is of particular importance. Motorway horizontal alignment, especially when the motorway is constructed in flat terrain, is composed from large circular and transition curves corresponding with high design speeds (Ilić et al. 2022). Combining shallow longitudinal grades, specific to flat terrain, with the cross grades nearing 0% in the inflection zones increases areas of pavement surfaces with low total gradients prone to aquaplaning. The sizes of these areas are highly dependable on the general longitudinal grade of the road, as reported by Charbeneau et al. (2008). So, these zones with both longitudinal and cross grades close to 0% are the areas where water ponds and puddles might be expected.

There are two methods of superelevation that could mitigate the problem of low total gradients in motorway inflection zones. The first one refers to the rolling crown pavement with the diagonal crown line, running from left to right pavement edge, providing that no pavement area with the cross grade lower than 2.5 % could exist in the inflection zone. Rolling crowns in concrete pavement have not yet been built in Europe, so currently their application is limited to asphalt pavements. The second method is based on variable superelevation rate along the superelevation runoff length. In this case, higher relative grade must be deployed in the central part of the inflection zone (i.e., the area around the inflection point), thus shortening the stretch of pavement with insufficient cross grades.

When it comes to motorways and expressways, the median is usually kept horizontal, while the carriageways are rotated separately around the median outer edges. Pavement surface drainage problems may appear due to potential lack of adequate longitudinal grade in superelevation transition section, particularly in the inflection zones of reverse curves or “S” curves. These problems may occur when the effective relative grade (superelevation grade) is close to longitudinal grade of the road, but with the opposite sign. It results in the outer edge of pavement having negligible longitudinal grade, which further leads to poor pavement surface drainage, especially on curbed cross sections as stated by AASHTO (2018).

To provide efficient drainage in road inflection zones, longitudinal grade of carriageway edges, or curbs, must be steeper than minimal hydraulic grade efficiently conveying stormwater flow. According to Serbian road design standards (PE Roads of Serbia (2011)), the absolute minimum longitudinal grade of curbs along the pavement edges must be 0.3 % or higher. Unlike Serbian standards, the absolute minimum longitudinal grade of the pavement edge in German design guidelines for motorways RAA (FGSV (2011)) is limited to 0.2 %. However, the German RAS-L allows the application of such a small pavement edge grade only in exceptional cases, while in regular design practice the minimum longitudinal grade of 0.5% should be applied.

The most effective design solution, which ensures an efficient drainage of pavement surface, is occasional application of negative cross slope in motorway curves. Nevertheless, this design solution is applicable only when the motorway horizontal alignment is composed of very large circular curves with radii $R \geq 5000$ m. With the cross grade directed continuously to the outer carriageway edges, superelevation transitions and, consequently, all critical zones prone to aquaplaning can be avoided completely (Lippold et al. (2019)).

Numerous studies addressing the impact of climate change on transportation infrastructure have been published, but only a few of them tackled possible impact of climate changes on the pavement superelevation and aquaplaning occurrence. In their study, Hildebrand and Morrall (2021) discuss how climate changes affect the pavement cross grade, in relation to road safety. Contemporary methods for cross grade calculations and superelevation concepts should be revised according to climate changes, particularly on motorways and high class roads with wide carriageways.

2. Pavement superelevation methods in motorway inflection zones

In Serbia, like in most European countries, motorway carriageways are superelevated around the outer median edges. In this manner, the general median cross grade is equal to zero, which has both technical and aesthetic advantages. In the case of motorways in mountainous terrain, opposite carriageways might be separated, but still superelevated around their inner edges.

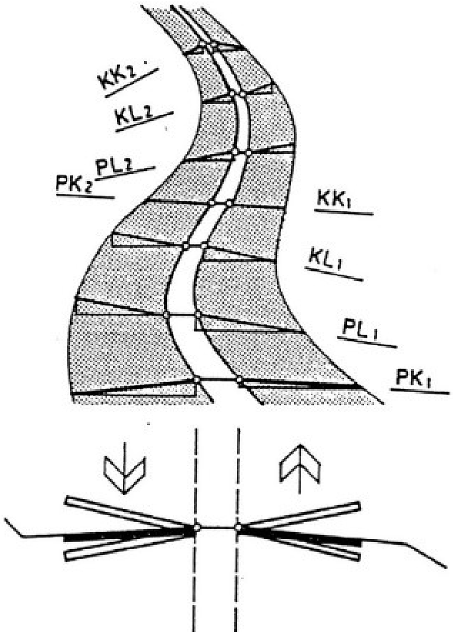


Fig. 1. Motorways' carriageway superelevation around median edges (Katanić et al. (1983)).

Key parameter, telling the intensity in cross grade change, is relative grade of a carriageway edge i_{rv}. The relative grade i_{rv} [%] represents the difference between the longitudinal grade of the carriageway edge and the longitudinal grade along the axis of carriageway rotation. It is calculated as:

$$i_{rv} = \frac{i_{pk} - i_{po}}{L_p} \cdot B \qquad (1)$$

where:

i_{pk} [%] - crossgrade of the carriageway at the end of the superelevation transition section (usually at the beginning of the circular curve - end of transition curve);

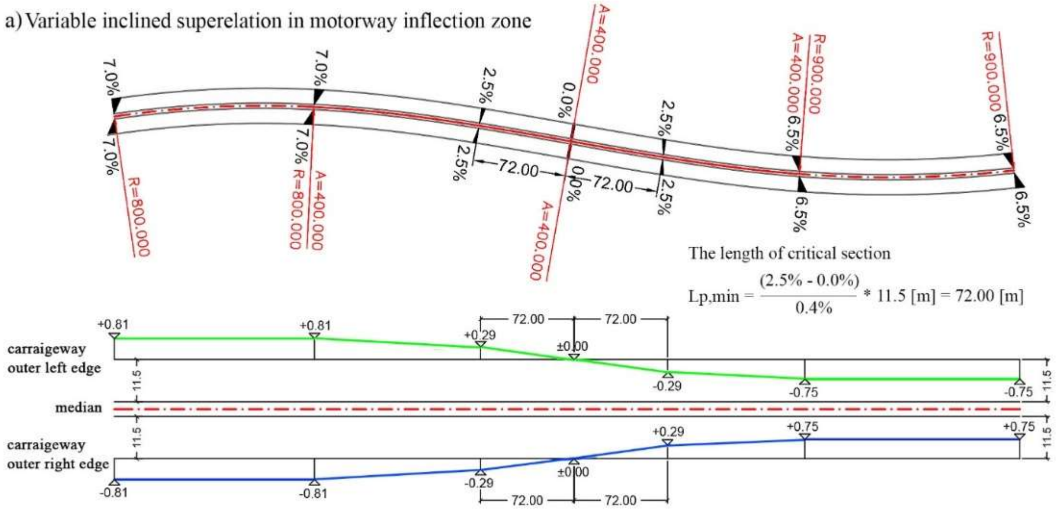
i_{po} [%] - crossgrade of the carriageway at the beginning of the superelevation transition section (i_{po} should be negative if it is in opposite direction in relation to the crossgrade i_{pk});

L_p [m] - superelevation development length or superelevation runoff length;

B [m] - Horizontal distance between the edge of carriageway and the axis of its rotation (carriageway width).

According to Serbian road design standards (PE Roads of Serbia (2011)), to avoid a rapid increase in crossgrade throughout the superelevation zone, the maximum relative grade $i_{rv,max}$ should not exceed the value of 0.9% for the motorway sections with design speed of 130 km/h. On the other hand, for the same road class, the minimum relative grade $i_{rv,min}$ is limited to 0.4%. If, on a long continuous superelevation transition section, typical for motorways, the relative grade (superelevation grade) is less than the minimum relative grade $i_{rv,min}$ (0.4%), it is necessary to apply a variable superelevation rate and divide the superelevation runoff length into two sections, as shown in Fig. 2a. In this case, the carriageway edges within the more critical first section (inner section), where the pavement crossgrade changes its direction from positive $i_{pk} = 2.5\%$ to negative $i_{pk} = -2.5\%$, must be constructed with a relative grade equal to the minimum $i_{rv,min}$. Along the second section (outer section), which represents the remaining length of the transition curve, reduced superelevation rate is applied until the crossgrade required by the next circular curve is met. Thus, the relative grade of carriageway edges along the less critical outer section is always less than the minimum relative grade $i_{rv,min}$, but the pavement cross grades in this section are always equal to or higher than 2.5 %.

a) Variable inclined superelation in motorway inflection zone



b) Rolling crown pavement in motorway inflection zone

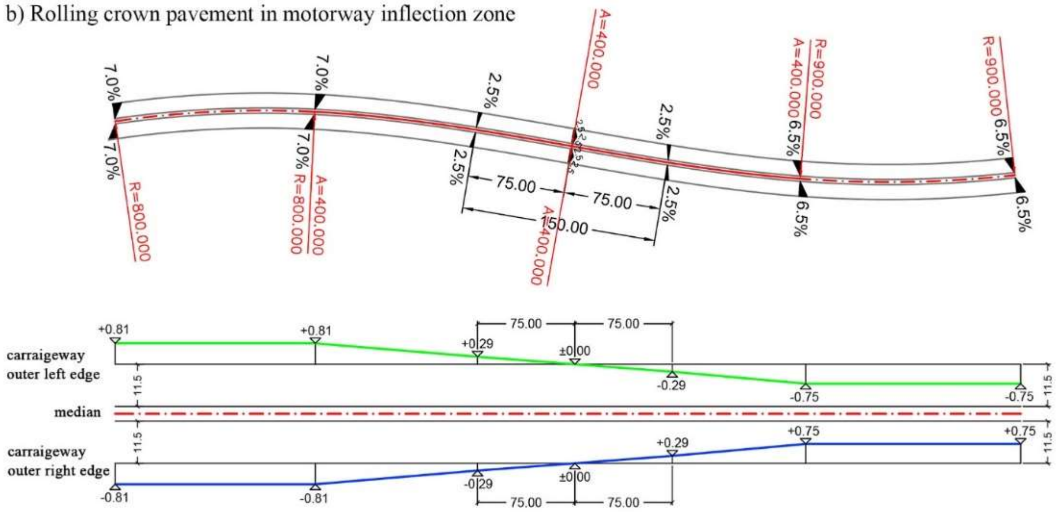


Fig. 2. Carriageways' superelevation in motorway inflection zone: (a) variable inclined superelevation; (b) rolling crown pavement.

A lack of adequate longitudinal grade in the superelevation transition section further increases the risk of aquaplaning. The worst case scenario is when the longitudinal grade of carriageway axis of rotation is approximately equal, but of opposite sign, to the effective relative grade. It results in the outer edge of carriageway having negligible longitudinal grade, which can lead to poor pavement surface drainage, especially on curbed cross sections in urban areas according to AASHTO (2018). Therefore, a minimum longitudinal grade of carriageway edges, regarding hydraulic runoff requirements, should be provided along the whole length of the motorway, including inflection zones in reverse curves. In Serbian road design standards (PE Roads of Serbia (2011)), the absolute minimum longitudinal grade of carriageway edges, regarding stormwater drainage requirements, is 0.3 %. Unlike Serbian standards, in German design guidelines for motorways RAA (FGSV (2011)) the absolute minimum longitudinal grade of the pavement edge is even smaller and stand at0.2 %.

In cases when absolute minimum longitudinal grade of the pavement edge cannot be met by using standard pavement superelevation concepts, the rolling crown pavement presents the only geometrical solution to the problem. The application of rolling crown pavement in motorway inflection zone is shown in Fig. 2b. Grading plan of the same motorway inflection zone where the rolling crown pavement was deployed, is displayed on a larger scale in Fig 3. As can be seen from Fig. 3, contours of the pavement surface break along the diagonal crown line.

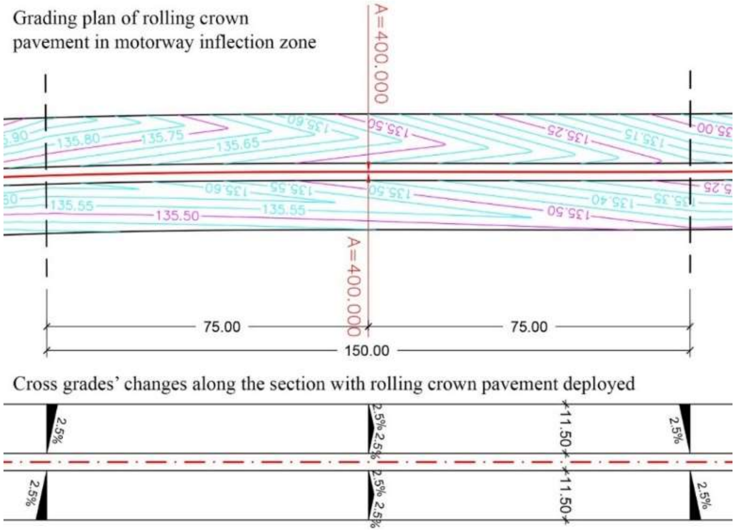


Fig. 3. Rolling crown pavement - grading plan

Application of rolling crown pavements in inflection zones is specific for German and Swiss design practice. As shown in Fig. 4, the ridge dividing the sloped pavement surfaces represents the diagonal crown line running from left to right carriageway edge. Hence, the cross section of the motorway carriageway, which is taken exactly from the inflection point, resembles a crown (roof) with sloped pavement surfaces falling down on both sides. According to Serbian road design standards (PE Roads of Serbia (2011)), the length of the section where the rolling crown pavement is constructed, depends on the design speed V_r. Similarly, in German design standards (FGSV (2011)), this length is calculated from motorway's design speed V_r and carriageway width B:

$$L_v = 0.1 \cdot B \cdot V_r \tag{2}$$

where:

L_v [m] - the length of zone where the rolling crown pavement is installed

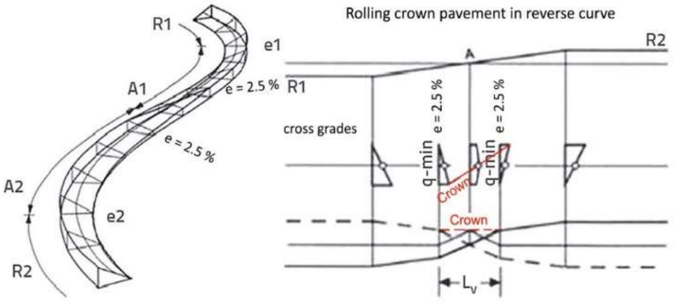


Fig. 4. Rolling crown pavement deployed in reverse curve inflection zones on German roads (adopted from TUD. (2013)).

To avoid dynamic problems, in some German federal states, even the speed limit is imposed in the zones where rolling crown pavement is constructed. However, according to traffic accident data acquired from these sections, setting the speed limit is not necessary (Lippold et al. (2019)). Therefore, comprehensive research on the rolling crown pavement impact on driving dynamics, particularly in terms of recommended operating speeds, should be undertaken.

Main disadvantage of the rolling crown pavement is rather complicated construction in the field. In fact, it is not possible to build such a diagonal form of sloped pavement surfaces completely by a paver and there are always some small wedge-shaped pavement areas to be finished manually.

3. Impact of pavement superelevation concept on aquaplaning occurrence in road inflection zones

In general, aquaplaning risk assessment includes two steps. The first step is calculating the depth of a flow, or water film thickness over a pavement surface, while the second step is comparing the calculated water film thickness to critical water film thickness. Critical water film thickness is actually the depth for which, for exact operating speed, aquaplaning occurs. Previous studies done by Herrmann (2008), Cerezo et al. (2010), and Micaelo et al. (2015), clearly state that, among all the relevant parameters, such as pavement surface geometry, pavement texture and rutting, rainfall intensity and tyre tread depth, the water film depth (WFD) stands out as the most important factor causing the aquaplaning. Accordingly, the accuracy of WFD calculation for various pavement superelevation scenarios is crucial for the reliable assessment of aquaplaning potential.

Burlacu et al. (2018) used Pavement Surface Runoff Model (PSRM) software, developed by Technical University in Stuttgart, to analyze several types of pavement superelevation concepts applied in inflection zones on two-lane roads and motorways with shallow longitudinal grades. Their software simulation has demonstrated that significant amount of water remained in the inflection zones of motorways which were designed with gentle longitudinal grade of 0.2% and with traditional superelevation concept applied. However, as can be seen in Fig. 5, when rolling crown pavement is deployed in the same motorway inflection zone, resulting water film depths (WFD) in critical central parts of reverse curves are significantly reduced. The results of PSRM simulation confirmed that the rolling crowns have a high drainage efficiency, even when they are constructed on motorway sections with longitudinal grades close to zero, because there are no cross grades lower than 2.5 % throughout the entire inflection zone. Despite this considerable advantage, due to noticeable impact on driving dynamics, construction of rolling crown pavement on high-speed motorway sections is not generally accepted yet.

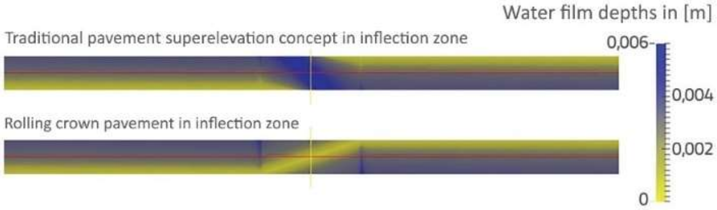


Fig. 5. PSRM software simulation of WFDs for various pavement superelevation concepts in motorway inflection zone (Burlacu et al. (2018)).

4. Climate change impact on water film depth assessment in superelevation transition section

Superelevation concept strongly affects total pavement gradient, the length of surface flow path, and WFD values in critical motorway inflection zones. In past decades, numerous theoretical and empirical methods for the prediction of the WFDs over sloped pavement surfaces were developed. The most popular method for water film depth assessment was developed by Gallaway et al. (1972) for the USA Federal Highway Administration (FHWA). The metric version of the Gallaway equation used for WFD calculation is:

$$D = \frac{0.103 \times T^{0.11} x\, L^{0.43} x\, I^{0.59}}{S^{0.42}} - T \tag{3}$$

where:

D [mm]	- water film depth above the top of pavement texture
T [mm]	- average pavement texture depth
L [m]	- length of surface flow path
I [mm/h]	- rainfall intensity
S [%]	- grade of surface flow path

Since the Gallaway equation is an empirical formula based on the experimental results, it has certain limits regarding the range of values that can be used as input parameters:

- surface flow path length of up to 14.6 m

- rainfall intensity of up to 50.8 mm/h
- grades of up to 8%

Additionally, the Gallaway method is one-dimensional and can be used only to assess the depth of a flow along a single (zero width) flow path. Moreover, the Gallaway equation cannot calculate correct WFDs in cases where the flow of surface water changes its direction due to superelevation or due to cross grade changes, what actually occurs in inflection zones. In recent study, Ilic et al. (2024), demonstrated on practical example that surface flow paths in motorway inflection zones are significantly longer than the maximum length applicable by the Gallaway formula (14.6 m). Also, the study has shown that, by increasing both carriageway width and longitudinal grade, the differences in surface flow path lengths become even higher, thus seriously undermining the application of the Gallaway formula for accurate WFDs assessment on new motorway projects.

In most European countries, motorway stormwater drainage system is to be designed with the 10-year return period rainfall. Expected rainfall intensities in Serbia and the neighbouring countries, which correspond to 10-year return period, are considerably higher than maximum rainfall intensities recommended by Gallaway formula (50.8 mm/h). Due to increasing climate changes impact, rainfall intensity, representing one of the key input parameters for WFD assessment, has also been changed in recent decades. Gallaway equation is based on the experimental research carried out in the 1970s. Since the rainfall intensities have radically changed, not only in the USA, but also in the rest of the world, new data on rainfall intensities must be separately collected for specific climate zones.

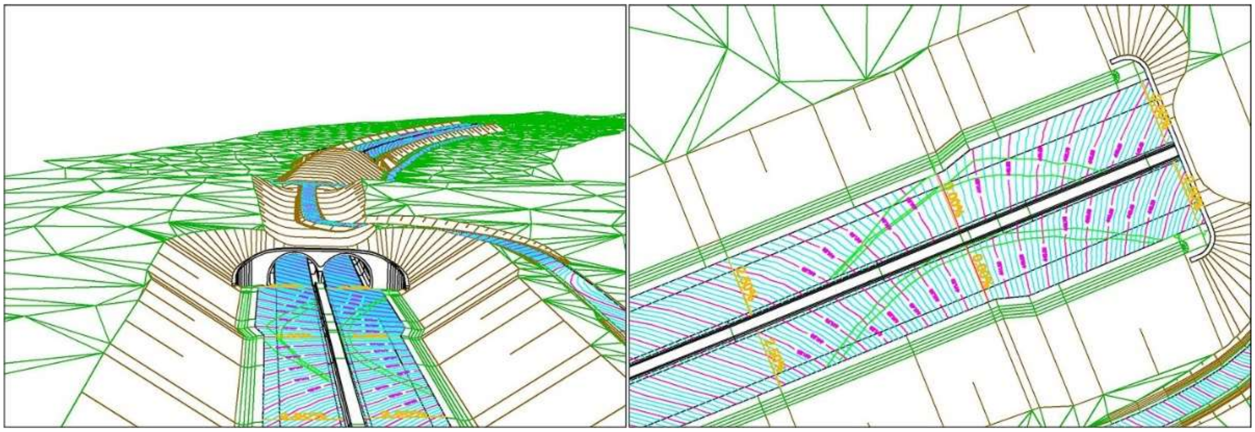


Fig. 6. Western portal of Unterflurtrasse Reigersdorf tunnel - Grading plan with water flow trajectories (Kassmannhuber et al. (1998)).

According to Serbian motorway design practices, critical rain is the one with the duration of 15 min and a return period of 10 years. It is equivalent to the rainfall intensity of 300-400 lit/sec/ha (27 to 36 mm). In recent years peak intensities of 500 lit/sec/ha has been observed. For road designers it is still questionable how to relate these peak values to the cumulative rainfalls lasting 15 min, which dictate the overall capacity of the drainage system. But, when it comes to WFD, the immediate action is needed. In Fig. 6 grading plan of the typical motorway inflection zone is shown, with several waterflow trajectories overlapped. This is the western portal of Unterflurtrasse Reigersdorf tunnel on A2 Süd Autobahn near Klagenfurt, Austria. Though the trajectories are quite long, exceeding 50m (way longer than those covered by Gallaway formula), concentration times are short. It means that the WFDs are heavily influenced by the increased peaking rainfall intensities expressed in litters/second/hectares (500 or more, for example). Consequently, not only the innovative geometrical solutions in superelevation zones do have to be exercised, but it may well happen that the overall capacities of inlets along the pavement edges (curbs) are to be reconsidered.

5. Conclusion

The most critical areas regarding surface drainage and aquaplaning risk are motorway inflection zones located in flat terrain, where low pavement cross grades are combined with shallow longitudinal grades. Adopted pavement superelevation concept strongly influences total gradients of the pavement surface and consequently the lengths of surface flow paths and resulting WFDs. Regarding drainage efficiency, construction of rolling crown pavements in central parts of long reverse curves proved to be very good design solution, but its impact on driving dynamics should be thoroughly investigated in the future. Widely used Gallaway's formula is not a reliable method for WFD calculations, as the surface flow path length applicable by Gallaway is much shorter than the real lengths expected in the European motorway's inflection zones. An additional concern is reliability of stormwater data, particularly rainfall intensities, as a key input parameter for accurate WFD assessment. This issue becomes more important with the climate change trends and their impact on the road infrastructure taken into consideration.

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