Assessing Aquaplaning Thresholds through Critical Vehicle and Freeway Geometric Parameters

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ABSTRACT

Wet pavement conditions, exacerbated by adverse weather, play a crucial role in roadway safety, contributing annually to numerous vehicle crashes. This study examines the dynamic aquaplaning phenomenon along 2lane, 3lane and 4lane urban motorways, aiming to assess key aquaplaning thresholds of water film thickness above the pavement texture (WFT) and aquaplaning speed (APS), respectively. In total, 225 alignments of various combinations of geometric parameters were examined. These were also related with a selected range of additional parameters, involving pavement surface characteristics, vehicle parameters, and rainfall intensity rates, resulting in 18225 combinations in total. The aquaplaning assessment was performed by utilizing the method developed by Gallaway, where in addition, the critical drainage paths were determined from the algebraic sum between the longitudinal grade and the superelevation rate in 3D roadway geometry. The applied multiple linear regression analysis revealed a high prediction precision for both WFT and APS models. In addition, the performed elasticity analysis revealed that critical parameters for WFT are rain intensity rates, followed by grade, where critical parameters for APS are tire pressure, followed by pavement texture. The present research aimed to quantitatively define potential critical conditions related to key road and vehicle parameters, and ultimately introduce evidence based variable speed limits. Further work on the implementation of reliable variable speed limits should adopt a more integrated and holistic approach, taking into account additional conditions that further restrict vehicle speed (e.g. skidding, traffic conditions, visibility, detailed driver behavior assessment, etc.).

Keywords: aquaplaning, water film thickness, aquaplaning speed, urban motorways, linear regression, elasticity analysis.

INTRODUCTION AND PROBLEM STATEMENT

Adverse weather is proven to be a major determinative factor as far as roadway operation safety is concerned. Rainy pavements contribute to about 10% of vehicle crashes in the United States, injuring over 210,000 people and killing over 2,400 each year [1]. In particular, rainy weather combined with various intensity rates may lead to even more critical safety violations.

Speed distributions under such weather conditions are generally expressed by comparatively lower mean speeds and substantial speed variations, i.e. volatility, compared to normal (wet) pavement conditions. Even under mild rainfall intensity, the anticipated reduction in drivers' visibility and pavement adhesion may potentially lead, under certain circumstances, to the appearance of the phenomenon of aquaplaning, also known as hydroplaning, and thus result in vehicle control instability and control loss.

Besides aquaplaning, a similar steering-failure hazard that drivers may experience during vehicle motion on pavement surfaces with reduced friction supply, not necessarily wet and/or rainy, is vehicle skidding.

Both skidding and aquaplaning are critical and undesirable conditions. The difference between the two phenomena, is that skidding occurs while the tires are still in contact with the pavement, typically as a result of excessive vehicle braking or acceleration (friction demand exceeds friction supply), whereas aquaplaning initiates from a reduced or complete absence of contact between tire and pavement [2]. This form of hydroplaning, known as dynamic hydroplaning is the most frequent type and generally occurs for vehicle speeds typically over 70km/h.

Aquaplaning phenomena may also occur at any speed on pavements with little or no micro-texture where even a very thin film of water may separate the moving tire from pavement; this type of aquaplaning is known as viscous aquaplaning. Additionally, on aircraft runways, reverted rubber aquaplaning makes its appearance, caused by the friction between the tires and the pavement, generating excessive heat [3]. The simultaneous combination of aquaplaning and skidding is called partial aquaplaning. The present research addresses the dynamic aquaplaning phenomenon.

Although variable speed limit control has been increasingly applied as an active traffic management strategy to harmonize vehicle speed and improve safety at curved road sections under adverse weather conditions, its implementation has not been associated yet with the interaction between road, user and vehicle parameters for various rain intensity rates.

In light of the above, the objective of the present study is to assess key aquaplaning thresholds for various rainfall intensity rates associated with the critical case of motorways (freeways) with extensive carriageway width, by examining various alignments in 3D (plan view, longitudinal profile and superelevation design of divided freeways with variable carriageways), jointly with pavement surface characteristics (texture depth), vehicle (tire tread depth and pressure) and user parameters (spindown of the rotational speed at the initiation of hydroplaning).

METHODOLOGY

Aquaplaning is assessed through two basic parameters, which in turn depend on additional factors such as roadway geometry, environmental conditions, and driver – vehicle interactions. These parameters are:

- Water film thickness above the top of pavement texture (WFT)
- Aquaplaning speed (APS)

WFT is defined as the thickness of water measured from the top of the pavement texture asperities, subtracted by the Mean Texture Depth (MTD) or Mean Profile Depth (MPD) (**Equation 1**). The way WFT is related to the total water flow (TWF) is visualized in **Figure 1**.

$$WFT = TWF - MTD \tag{1}$$

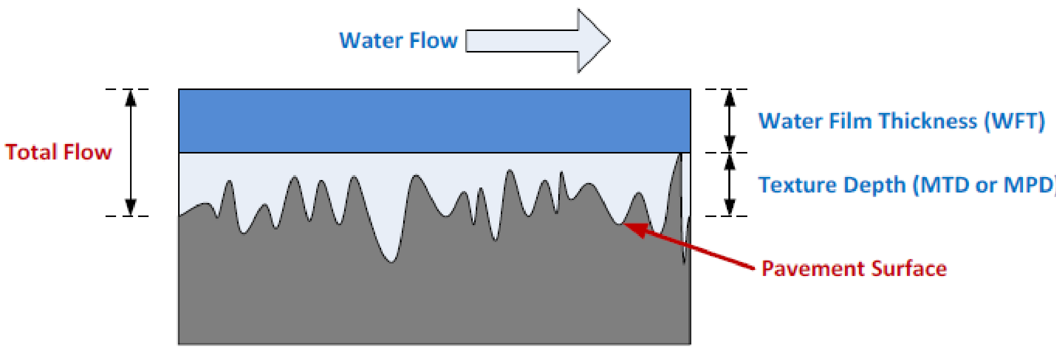


Figure 1 Relation between WFT, TWFT and MTD [3]

Two types of methods for addressing WFT and APS can be found in the literature; those based on empirical data and those developed via analytical aquaplaning modeling. The main advantage of analytical models over the respective empirical ones is the handling of compound geometric parameters (curved sections, grades, superelevation rates, etc.), as well as detailed tire - pavement interactions (e.g. rutting, etc.).

However, certain empirical models, with respect to the range of the assessed parameters, have been proven to produce accurate results (e.g. [4, 5]). These findings can be justified by the fact that these empirical models have undergone extensive laboratory testing and, moreover, certain improvements have been incorporated to assess a more precise grade calculation in areas of compound alignments.

Such a case is the Gallaway (1979) [6] formula; one of the most widely accepted empirical models for determining WFT [2, 3, 7, 8]. The aquaplaning risk through the Gallaway method is assessed by determining the expected water film thickness for a given drainage path across the carriageway and comparing it against acceptable design limits, which in general fall between 3.3mm [2] and 4.0mm [6], or even 5mm for speeds below 80km/h [8]. It should also be noted that the Gallaway method [6] is limited in assessing WFT along a single flow path (zero width). Flow velocity and width or spread of the flow over the pavement surface are ignored [9].

The drainage path is the rainfall runoff trajectory that follows the steepest descent along the road pavement up to its edge line; longer drainage paths, in general require more time to accumulate rainfall water and result in higher water film depths.

The aquaplaning speed outputs are compared against the roadway's design speed and proposed speed limits based on other assessments that should be performed concurrently (vehicle skidding, stopping sight distance inadequacy, etc.).

In the present paper, the examined alignments are designed in accordance with the German RAA, 2008 [10] urban freeway design guidelines (EKA 3 Class).

Aquaplaning assessment is performed by utilizing the method developed by Gallaway et al (1979) [6], where in addition, the algebraic sum between the longitudinal grade and the superelevation rate is assessed in the 3D roadway geometry.

More specifically, the drainage path is determined through a predefined calculation step along the axis of the assessed road section, and consists of segmented routes, where each segment extracts the algebraic sum (vector pi) between the longitudinal grade and the superelevation rate. Drainage paths may have constant direction vectors only at areas where the grade and superelevation vectors are fixed.

Figure 2 shows the right carriageway of a left curved two-lane rural road section consisting of an entrance spiral curve followed by a circular arc. The road section initiates from point TS (tangent to spiral), following a tangent of a crowned superelevation (e_1 = -2.5%, negative). Due to pavement rotation, around the centerline, the superelavation rate reverses to e_2 = +2.5% (positive) at point TSa and reaches the constant value of e_3 (let e_3 = +e_{circ_arc}%, positive) at point SC (spiral to curve), where the curve radius is set to R. Assuming the pavement rotation axis located along an upgrade of s = +$s_{upgrade}$%, the algebraic sum pi of the right carriageway per design element at any lateral distance ai, measured from the pavement rotation axis [ai ≤ a, (a: distance between carriageway edge line and pavement's rotation axis – carriageway width without emergency lane)], is calculated as follows:

- Tangent area
  - $e = e_1 = -2.5\%$ (2)
  - $s = +s_{upgrade}\%$ (3)
  - $p_{ai} = p = \sqrt{s^2 + e^2}$ (4)
- Spiral area
  - $-2.5\% \leq e_x \leq +e_{circ\_arc}\%$ (5)
  - $s_{ai} = +s_{upgrade} + \Delta s \frac{a_i}{a}$ (6)
  - $p_{ai} = \sqrt{s_{ai}^2 + e_x^2}$ (7)

  where:

  $e_x = \frac{L_x \Delta s}{a} + e_1$ (8)

  $\Delta_s = \frac{e_3 - e_1}{L} a$ (9)

  $L = \frac{A^2}{R}$ (10)

  s_{ai}: Longitudinal grade at a lateral distance of a_i from the alignment's rotation axis (%)

  e_x: Superelevation rate at a distance x along the alignment's rotation axis from point TS (%)

  Δs: Relative grade at spiral area between longitudinal gradient along the carriageway edge line and longitudinal gradient (s) along the alignment's rotation axis (%)

  L: Spiral length (m)

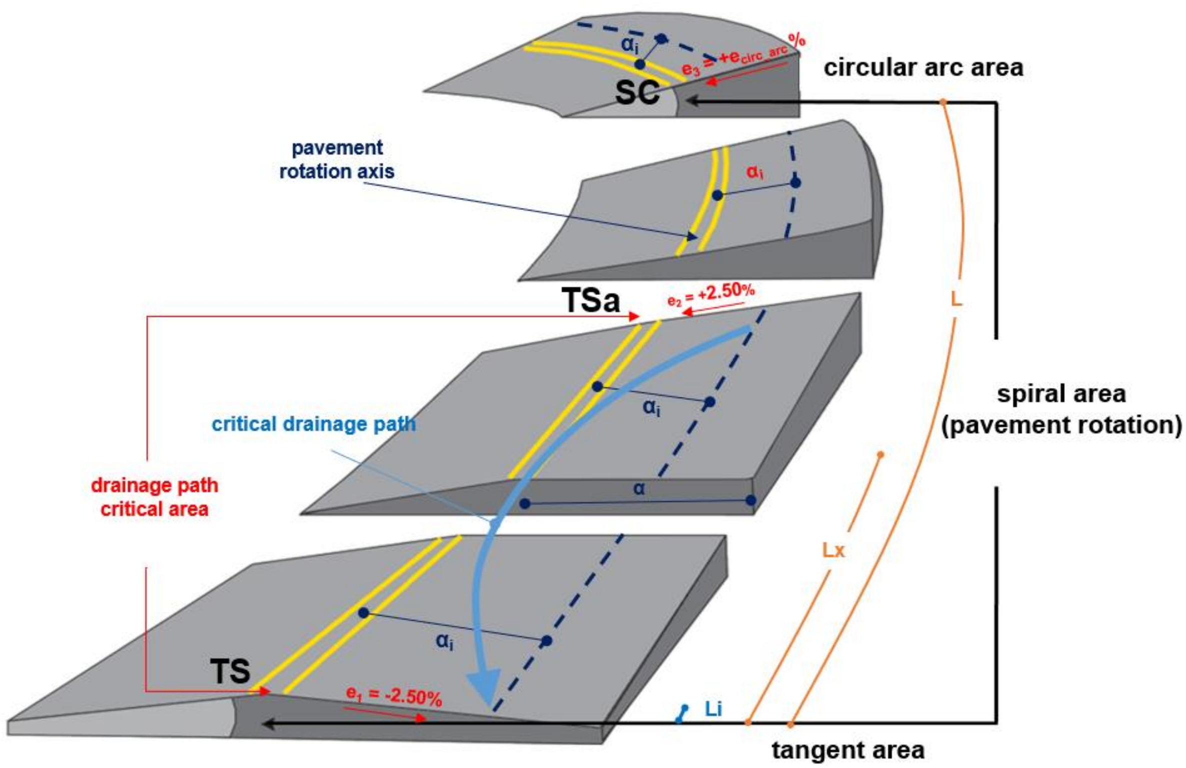
  A: Spiral parameter (m)

  L_x: Spiral length at distance x along the alignment's rotation axis from point TS (m)
- Circular arc area
  - $e = +e_{circ\_arc}\%$ (11)
  - $s_{ai} = s_{upgrade} \frac{R}{R + a_i}$ (-a_i for right curved alignments) (12)

$$\circ \quad p_{ai} = \sqrt{s_{ai}^2 + e^2} \tag{13}$$

At the roadway's tangent area (before point TS), as described through **Equation 2 - Equation 4**, the vector of the compound grade p, with respect to fixed grade and superelevation rates, has a constant direction.

Moreover, as seen in **Figure 2**, at the area between points TS and TSa, where the pavement rotation reverses the superelevation rate from negative (e_1 = -2.5%) to positive (e_2 = +2.5%), the critical drainage path corresponding to the lateral distance "ai" is formed. This is due to the fact that the direction of the drainage path shifts from outward to inward and outward again, following a curved route, and thus increasing its length.



Note. The arrow in the critical drainage path for the ai lateral distance indicates water flow direction.

Figure 2 Pavement rotation along a left curved, upgrade road section between tangent and curve

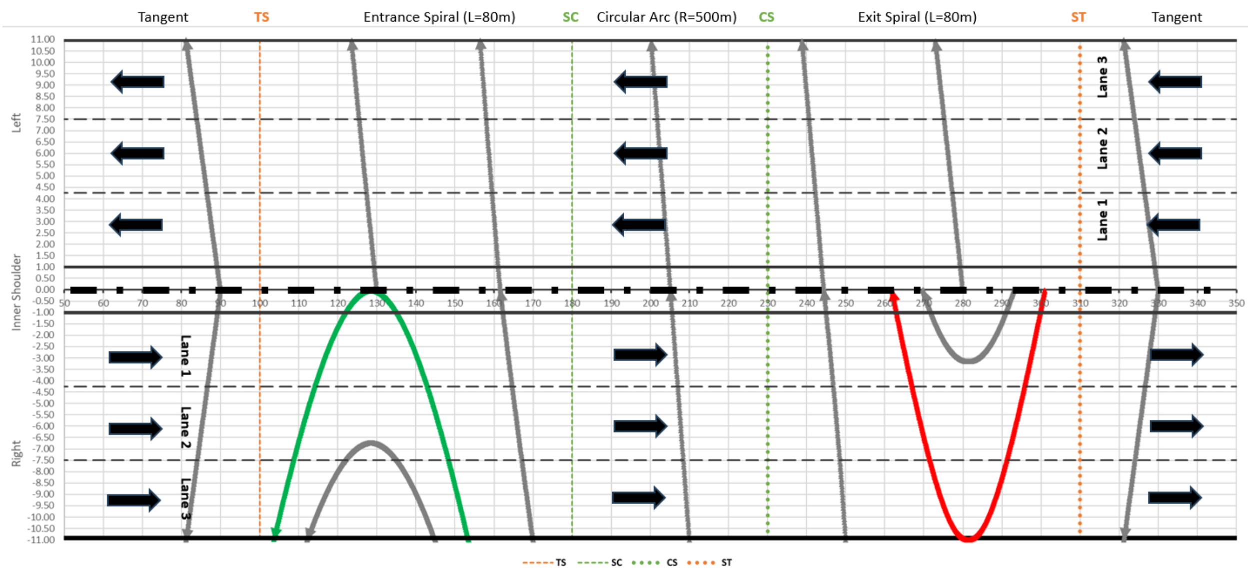
In the present analysis, the determination of the critical drainage paths, along the chainage of the alignment, consisted of a calculation step set to 0.05m (Li = 0.05m).

Such curved drainage paths are further increased with steep grades, a fact that in turn amplifies the risk of aquaplaning. In general, in order to reduce the aquaplaning potential, the drainage paths should be limited to a length of approximately 60m [2, 8].

Based on the above equations, **Figure 3** shows the calculated drainage paths along a 3+3 lanes left curved divided road section (2x11.00m carriageway) consisting of an entry and exit spiral curve and a circular arc in between.

As seen in **Figure 3**, the drainage paths in general cross the pavement in the lateral direction (grey lines). However, at the areas where the superelevation rotates from outwards to inwards and vice versa, the drainage paths form curved trails that are maximized within the green and red areas, respectively. These drainage paths (approximately 55m), drastically increase the potential of aquaplaning hazards.

Nevertheless, in terms of safety, it should be emphasized that the area with the red drainage path is more critical than the respective green one (**Figure 3**), because the water runoff starts and terminates at the inner shoulder area, adjacent to the roadway's passing lane, where higher speeds are observed.



Note. a=11.0m, $e_{tangent}$= -2.5%, e_{circ_arc}= +4.5%, s= +2.0%. TS: tangent to spiral, SC: spiral to curve, CS: curve to spiral, ST: spiral to tangent. Grey arrows indicate direction of drainage path. Emergency lane omitted.

Figure 3 Drainage paths along a 3+3 lanes left curved divided road section

Based on the Gallaway [6] method, the WFT and APS formulas are as follows:

$$\mathrm{WFT} = 0.103 \cdot \frac{\mathrm{TXD}^{0.11} \cdot \mathrm{L}^{0.43} \cdot \mathrm{I}^{0.59}}{\mathrm{SG}^{0.42}} - \mathrm{TXD} \tag{14}$$

where:

WFT: Water film thickness above the top of pavement texture (mm)

TXD: Average pavement texture depth (mm)

L: Length of drainage path (m)

SG: Best single grade representation of the drainage path (see below) (%)

I: Excess rainfall intensity, which is actual rainfall intensity minus the infiltration rate or permeability of the pavement surface (mm/hr)

As already mentioned, the grade of the drainage paths is constant only at the tangent area, where along the curved sections, the so called "equal area grade" is applied, which is characterized as the "best single grade representation of the drainage path" and is calculated via the following steps [2]:

Step 1: Plot the longitudinal profile of the drainage path;
Step 2: Calculate the total area under the profile;
Step 3: Calculate the vertical ordinate of the equal area triangle, by dividing the area above by the length of the profile, and then multiplying by 2;
Step 4: Plot the new ordinate (at highest point on drainage path) and joining back to point of analysis;
Step 5: Calculate the slope of this line, expressed as a percentage (%).

$$APS = 1.609 \cdot [SD^{0.04} \cdot TP^{0.3} \left(1 + \frac{TTD}{\left(\frac{25.4}{32}\right)}\right)^{0.06} \cdot A] \qquad (15)$$

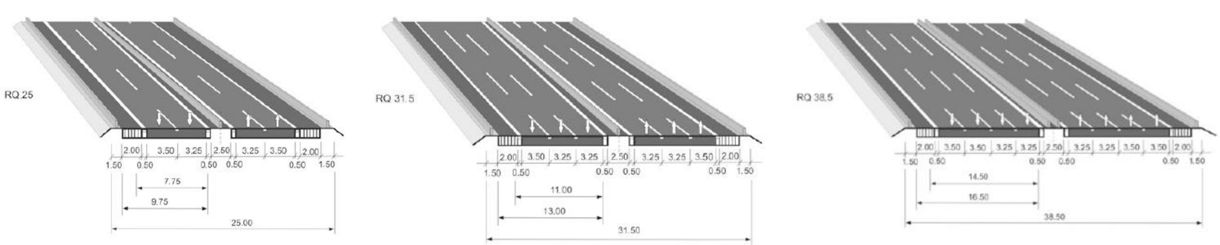
where:
APS: Aquaplaning speed (km/hr)
SD: Spindown of the tire rotational speed at the initiation of hydroplaning (%)
TP: Tire pressure (psi)
TTD: Tire tread depth (mm)

$$A: \max \left\{\frac{12.639}{WFT^{0.06}} + 3.50, \left[\frac{22.351}{WFT^{0.06}} - 4.97\right] \cdot TXD^{0.14}\right\} \qquad (16)$$

ANALYSIS AND RESULTS

As stated in the above, the aquaplaning assessment was performed based on the German RAA, 2008 [8] urban motorway (freeway) design guidelines (EKA 3 Class). As seen in **Figure 4**, three typical (divided) cross sections with 2lanes (RQ 25), 3lanes (RQ 31.5), and 4lanes (RQ 38.5) per direction of travel were examined respectively, where the emergency lane of 2.00m was also included.

The general design speed of EKA 3 motorways is 80km/h, where the speed limit is set up to 100km/h.



RQ 25 a = 7.75m, Δs_{min} = 0.78%
RQ 31.5 a = 11.0m, Δs_{min} = 1.10%
RQ 38.5 a = 14.5m, Δs_{min} = 1.45%

Note. "a": distance between carriageway edge line and rotation axis [emergency lane (hard shoulder) not included].

Figure 4 Typical cross-sections for EKA 3 motorways

The RAA, 2008 [8] control values for critical geometric values are as follows:

- Minimum curve radius: R_{min} = 280m
- Minimum spiral parameter: A_{min} = 90m
- Minimum superelevation rate at tangents: e_{min} = 2.5% (crown configuration)
- Maximum superelevation rate along circular arcs: e_{max} = 6.0%
- Maximum longitudinal grade at the pavement rotation axis: $s_{axis\ max}$ = 6.0%
- Minimum relative grade (Δs_{min}) between longitudinal gradient along the carriageway edge line and longitudinal gradient along the rotation axis at the areas between e_1 = -2.5% and e_2 = +2.5% :
  Δs_{min} = (0.1 a)% (a: distance between carriageway edge line and rotation axis)

Critical locations for hydroplaning are areas along the axis rotation between positive and negative superelevation rates. A wide range of geometric parameters were combined fulfilling the following constraints:

i. Utilization of three different radii (R_1=280m, R_2=550m, R_3=1000m) paired with applicable superelevation rates (e_1=6.0%, e_2=4.0%, e_3=2.5%), respectively, in line with RAA,2008 guidelines
ii. $R/3 \leq A \leq R$
iii. Utilization of increasing axis grade values from 0.0% up to the maximum value of 6.0%, reserving (for drainage adequacy) a minimum compound grade of 0.50% at the area of the carriageway edge line during pavement rotation between positive and negative superelevation rates
   - ✓ The following formula applies algebraically:
     $$s_{edge\ line} = s_{axis} + \Delta s \geq 0.5\% \qquad (17)$$
     from which the minimum grade at the pavement rotation axis can be determined as follows:
     $$\text{RQ 38.5: } s_{axis\ min} = 2.0\% \qquad (18)$$
     $$\text{RQ 31.5: } s_{axis\ min} = 1.6\% \qquad (19)$$
     $$\text{RQ 25: } s_{axis\ min} = 1.3\% \qquad (20)$$

With respect to the road geometry limitations mentioned above, and combining different design parameters as shown in **Table 1**, 75 alignments were developed per cross section type [(3 different radii values associated with respective superelevation rates) x (5 different lengths of spirals with respect to the $R/3 \leq A \leq R$ rule) x (5 different grade values with respect to the minimum grade value of 1.6%)]. In order to examine all three typical cross-sections for EKA 3 motorways [RQ 25 (2x2 lanes), RQ 31.5 (3x3 lanes), and RQ 38.5 (4x4 lanes)], in total 225 alignments were developed.

Additional parameters for the aquaplaning investigation involved the pavement texture depth (TXD), tire tread depth (TTD), spindown effect (SD), and tire pressure (TP), as well as rain intensity levels (RI). In order to investigate thoroughly their potential effect, a selected range based on literature findings was assessed as follows:

- TXD (mm): 0.5, 1.0, 1.5 [3]

- TTD (mm): 0.5, 1.0, 1.5 [6, 11]
- SD (%): 10 [3, 6]
- TP (psi): 24, 30, 36 [7, 11]
- RI (mm/h): 40, 80, 120 [3, 9]

TABLE 1 Utilized Geometric Parameters of the examined alignments

Note. $s_{axis\ min}$ (%) value, refers to the additional minimum grade investigated which depend on the cross section type [see Eq.(18) – Eq.(20)].

R (m)	A/R	e (%)	s (%)
280	0.33, 0.40, 0.60, 0.80, 1.00	6.0	$s_{axis\ min}$, 3.0, 4.0, 5.0, 6.0
550		4.0	
1000		2.5	

Overall, 18225 combinations were examined for the determination of water film thickness above the top of pavement texture (WFT) and aquaplaning speed (APS) values, respectively. The process is based on defining the critical drainage path per case.

In order to assess the significance in terms of involvement degree of the critical parameters stated above, it was decided to implement multiple linear regression for both water film thickness (WFT) and aquaplaning speed (APS) outputs.

Linear regression is a widely known, simple technique used to model a linear relationship between a continuous dependent variable and one or more independent variables [12]. As a result, regression models were developed to examine the correlation of WFT and APS against road geometry parameters.

To complement the developed models, elasticity analyses were also conducted. As defined in practice, elasticity analyses allow for the quantification of the response of the dependent variable for a 1% change of an independent continuous variable.

When dealing with independent categorical variables, it is meaningful to implement pseudoelasticities to obtain the incremental changes that are incurred as a result of category changes in the categorical variables [12].

By using elasticity (and pseudo-elasticity) analyses, the influence of each variable on WFT and APS was explicitly quantified. Following [12], the elasticity (ei) of a dependent variable Y with respect to a continuous independent variable X, which has a regression coefficient β, can be defined as follows:

$$e_i = \beta_i \frac{X_i}{Y_i} \approx \frac{\partial X_i}{\partial Y_i} \frac{X_i}{Y_i} \qquad (21)$$

The absolute elasticities can be rescaled to fit the range of all independent continuous variables, by setting the lowest value to 1 and adjusting the rest of the variables in proportion with their absolute score. It was decided that it was not appropriate to adjust pseudoelasticities alongside elasticities because the increases in independent variables are not comparable.

The developed models' descriptive statistics and coefficients for WFT and APS are shown in **Table 2** and **Table 3**, respectively.

TABLE 2 Descriptive statistics and coefficients for water film thickness (WFT)

Regression Statistics	
Multiple R	0.981
R Square	0.963
Adjusted R Square	0.963
Standard Error	0.275
Observations	18225

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	35299	8825	116968	0
Residual	18220	1375	0		
Total	18224	36674			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Elasticity*	*Relative Elasticity*
Intercept	1.643	0.012	136.456	0.000	1.620	1.667		
s	-0.367	0.001	-275.241	0.000	-0.370	-0.364	-0.467	1.000
TXD	-0.411	0.005	-82.567	0.000	-0.421	-0.402	-0.127	0.273
RI	0.038	0.000	608.836	0.000	0.038	0.038	0.781	-1.673
a	0.097	0.001	131.131	0.000	0.095	0.098	0.317	-0.679

TABLE 3 Descriptive statistics and coefficients for aquaplaning speed (APS)

Regression Statistics	
Multiple R	0.982
R Square	0.965
Adjusted R Square	0.965
Standard Error	1.100
Observations	18225

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	606390	101065	83454	0
Residual	18218	22062	1		
Total	18224	628452			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Elasticity*	*Relative Elasticity*
Intercept	50.105	0.072	693.577	0.000	49.963	50.246		
s	0.537	0.005	100.570	0.000	0.527	0.548	0.026	1.000
TXD	8.148	0.020	408.046	0.000	8.108	8.187	0.099	3.812
RI	-0.060	0.000	-242.331	0.000	-0.061	-0.060	-0.060	-2.325
a	-0.156	0.003	-52.670	0.000	-0.162	-0.150	-0.021	-0.823
TP	0.821	0.002	493.449	0.000	0.818	0.824	0.302	11.625
TTD	2.788	0.020	139.632	0.000	2.749	2.827	0.034	1.319

DISCUSSION

As seen in **Table 2** and **Table 3**, the statistical analysis carried out for WFT and APS, utilizing linear regression, delivered high prediction precision [adjusted coefficient of determination values (R^2 >96%)], although not all the independent variables examined were statistically significant.

From the road geometry parameters point of view, only grade (s) and carriageway width (a) values were found statistically significant. From the WFT point of view, increasing grade and carriageway width causes drainage paths to flow more efficiently on one hand, but also expand their length on the other, thus resulting in a decrease and increase of WFT values, respectively. Regarding the effect of grade and carriageway width to APS, the opposite is experienced.

As far as WFT predictions are concerned, apart from the above independent variables (s and a), pavement texture depth (TXD) and rain intensity (RI) levels appear also significant. In addition, the contribution of tire pressure (TP) and tire tread depth (TTD) is also required in order to improve the accuracy of APS.

For both models, besides the identification of the parameters involved, elasticity analysis was performed to quantify their effects.

More specifically, it can be seen in **Table 2** that regarding WFT, the most critical parameter is RI, followed by grade. For example, by increasing by 1% the RI rate and grade value (s), the WFT value increases and decreases by 0.78% and 0.47%, respectively.

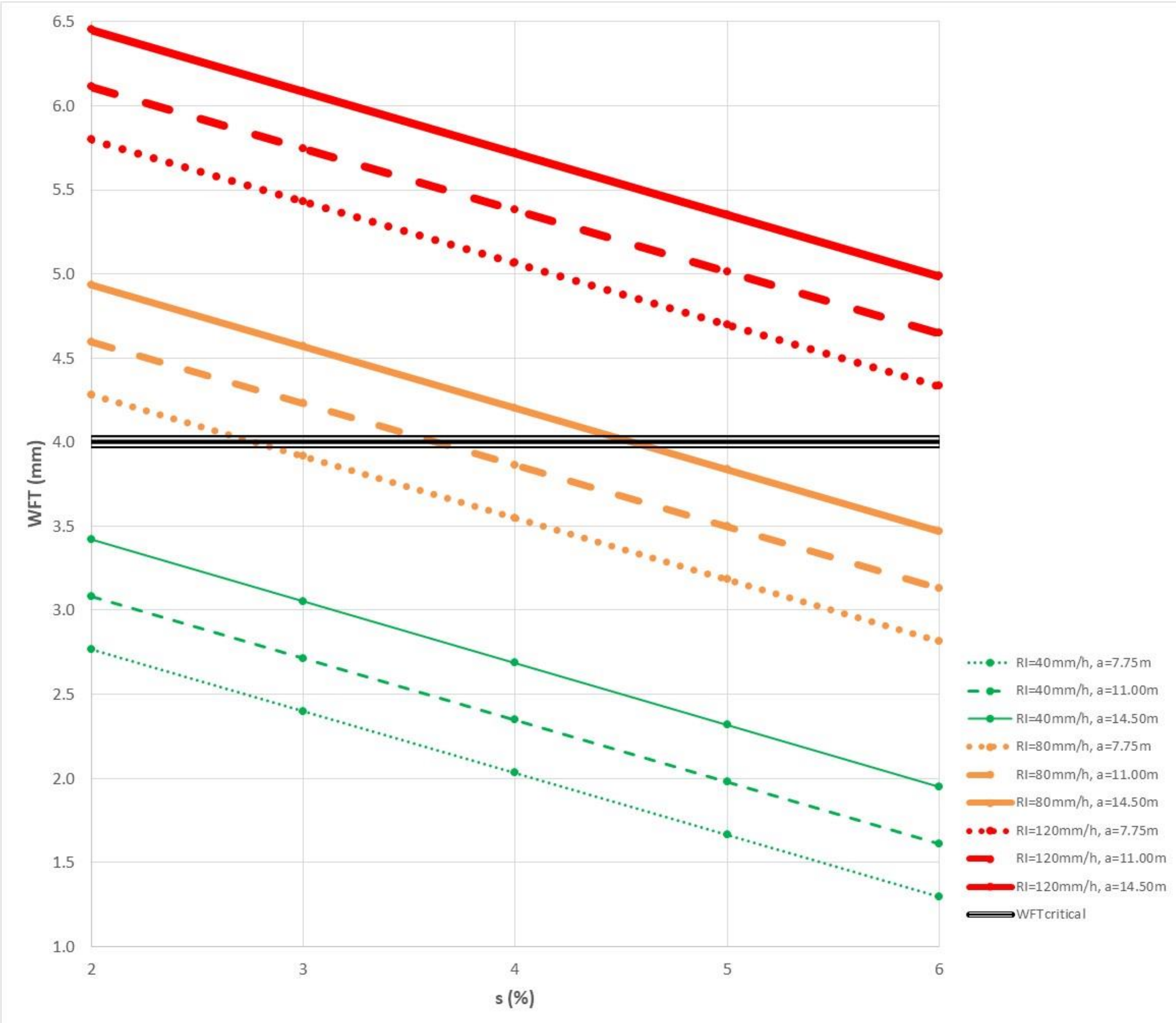
The respective critical factors that affect APS seem to be tire pressure and pavement texture depth with corresponding elasticity values of 0.30 and 0.10. Rain intensity rates, although considerable, affect (reversely) APS, ranking third in terms of significance (1% increase of RI results to 0.06% decrease in APS).

Pavement texture depth (TXD) seems to be a significant parameter for both WFT and APS. Based on the models shown in **Table 2** and **Table 3**, assuming tire pressure and rain intensity rates remain constant, an increase of the pavement texture depth by 0.5mm results in a decrease of the WFT and an increase of the APS values by approximately 0.2mm and 5km/h, respectively.

Figure 5 shows the values of WFT resulting from the model shown in **Table 2**, as a function of grade, assuming TXD parameters are set to their average value of 1.0mm. A general conclusion is that as grade becomes steeper, the aquaplaning potential seems to decrease. However, this finding needs to be also cross-examined with the respective drainage path length.

By examining **Figure 5** more closely, it can be seen that WFT values above the critical value of 4mm are experienced for RI rates approximately over 80mm/h, even for freeways with 2x2 lanes. More specifically, for RI=80mm/h, WFT>4mm result for grade values below approximately 2.8%, 3.7%, and 4.5%, corresponding to freeways with 2x2 lanes (carriage width 7.75m), 3x3 lanes (carriage width 11.00m), and 4x4 lanes (carriage width 14.50m), respectively. Therefore, for combinations of freeway cross sections, grade parameters, and rainfall intensity rates that result to WFT values above 4.0mm, the modeled APS values are not valid.

Such cases should be treated with cautiousness since lower speed values should be recommended as APS (e.g. the absolute minimum values of 60km/h or 70km/h). Alternatively, certain other options to reduce WFT are also available, such as introducing (longitudinal) crown lines among the lanes (preferably at the breakpoint of the emergency lane), or setting minimum thresholds for the pavement texture depth (TXD).



Note. TXD parameter set to its average value of 1.0mm.

Figure 5 Water film thickness (WFT) outputs.

CONCLUSIONS

The present research aimed to investigate critical aquaplaning thresholds utilizing three typical (divided) cross sections with 2lanes (RQ 25), 3lanes (RQ 31.5), and 4lanes (RQ 38.5) per direction of travel.

The assessment was performed by making use of the well-known Gallaway formula [6], enriched by analyzing the involved road geometry parameters in 3D, jointly with various rainfall intensity rates, pavement surface characteristics (texture depth), and vehicle parameters (tire tread depth and pressure), and assuming a typical value of user parameter (spindown of the rotational speed at the initiation of hydroplaning set to 10%).

The proposed methodology, based on the determination of the critical drainage path, revealed areas where aquaplaning potential is critical and must not be ignored. In total, 18225 combinations were examined for the determination of water film thickness above the top of pavement texture (WFT) and aquaplaning speed (APS) values, respectively.

The implementation of multiple linear regression revealed the significance of the involved parameters, where from the road geometry point of view, only grade (s) and carriageway width (a) values were found statistically significant.

The performed statistical analysis was complemented by respective elasticity analyses, in order to quantify the effects of the independent variables. The assessment revealed that critical parameters for WFT are rain intensity rates, followed by grade, where critical parameters for APS are tire pressure, followed by pavement texture.

Although the aquaplaning investigation was based on the German RAA, 2008 urban motorway design guidelines (EKA 3 Class), significant differences are not expected to be reported when other design guidelines are utilized. The reason is that the length of the critical drainage path, located at the superelevation rotation area from the positive normal value of e_1 = +2.5% to the respective negative value of e_2 = -2.5% and vice versa, depends partly on the corresponding length along the alignment (e.g. for AASHTO, tangent runout plus part of runoff length, where normal superelevation rate is set to e = 2.0%), and mostly on the grade value and utilized carriageway width.

The present research aimed to quantitatively define potential critical conditions related to key road and vehicle parameters, and ultimately introduce evidence based variable speed limits. The continuation of the work conducted on implementing reliable variable speed limits shall require a more integrated and holistic approach with the contribution of additional conditions that further restrict vehicle speed (e.g. skidding, traffic conditions, visibility, more detailed driver behavior assessment, etc.).

In conclusion, the fact that tire pressure is mostly critical for the determination of APS must be highlighted. Therefore, the proposed methodology is primarily applicable to connected and autonomous vehicles (CAVs), whose adoption can significantly enhance roadway safety by using real-time data to dynamically adjust speeds and navigate challenging conditions more effectively. CAVs can respond promptly to changing road conditions, reducing the risks associated with aquaplaning and skidding, whereas their ability to implement and adhere to variable speed limits based on real-time information ensures a safer driving environment under adverse weather conditions.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: SM, AK, VM, AT; data collection: SM, AK, VM, AT; analysis and interpretation of results: SM, AK, VM, AT; draft manuscript preparation: SM, AK, VM, AT. All authors reviewed the results and approved the final version of the manuscript.

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