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Identifying Areas on the Pavement Where Rain Water Runoff Affects Motorcycle Behavior

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Abstract**—**It is very well known that certain vertical and longitudinal slopes have to be assured in order to achieve adequate rainwater runoff from the pavement. The selection of longitudinal slopes, between the turning points of the vertical curves that meet the afore-mentioned requirement does not ensure adequate drainage because the same condition must also be applied at the transition curves. In this way none of the pavement edges' slopes (as well as any other spot that lie on the pavement) will be opposite to the longitudinal slope of the rotation axis. Horizontal and vertical alignment must be properly combined in order to form a road which resultant slope does not take small values and hence, checks must be performed in every cross section and every chainage of the road. The present research investigates the rain water runoff from the road surface in order to identify the conditions under which, areas of inadequate drainage are being created, to analyze the rainwater behavior in such areas, to provide design examples of good and bad drainage zones and to track down certain motorcycle types which might encounter hazardous situations due to the presence of water film between the pavement and both of their tires resulting loss of traction. Moreover, it investigates the combination of longitudinal and cross slope values in critical pavement areas. It should be pointed out that the drainage gradient is analytically calculated for the whole road width and not just for an oblique slope per chainage (combination of longitudinal grade and cross slope). Lastly, various combinations of horizontal and vertical design are presented, indicating the crucial zones of bad pavement drainage. The key conclusion of the study is that any type of motorcycle will travel for some time inside the area of improper runoff for a certain time frame which depends on the speed and the trajectory that the rider chooses along the transition curve. Taking into account that on this section the rider will have to lean his motorcycle and hence reduce the contact area of his tire with the pavement it is apparent that any variations on the friction value due to the presence of a water film may lead to serious problems regarding his safety. The water runoff from the road pavement is improved when between reverse longitudinal slopes, crest instead of sag curve is chosen and particularly when its edges coincide with the edges of the horizontal curve. Lastly, the results of the investigation have shown that the variation of the longitudinal slope involves the vertical shift of the center of the poor water runoff area. The magnitude of this area increases as the length of the transition curve increases.

Keywords**—**Drainage, motorcycle safety, superelevation, transition curves, vertical grade.

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I. INTRODUCTION

THE present research investigates the condition under which the rain water runoff from the road surface potentially affects motorcycle behaviour, a critical process which under certain circumstances might lead to hydroplaning and loss of visibility from splash and spray whereas ponded water may result in dangerous torque levels on vehicles and ultimate loss of vehicle control. However, all of these side effects require the evaluation of other parameters, e.g. rain intensity, calculation of water ponded depth, extent of crucial area etc.

It is very well known that three of the most important factors affecting hydroplaning are the pavement cross slope, the vertical grade and the width of the pavement. These factors which belong to the roadway characteristics affect the water flow depth [1]. Previous researches relevant to the rain water runoff aimed at identifying bad drainage areas along the pavement, analyzing the behavior of rain water in such areas and providing examples of how design choices generate good and bad drainage [2]-[4].

According to the Greek Road Design Guidelines Manual, chapter 3 and the American Association of State Highway and Transportation Officials, rain water drains adequately from the road surface, when the difference between the longitudinal slope and the cross slope is more than 0.5% [5], [6]. In particular, the following equation must be applied:

$$s - \Delta s \geq 0{,}5\% \qquad (1)$$

where: s [%] = longitudinal pavement slope, and Δs [%] = additional slope on edge line.

In a more recent study [4] Kaliabetsos suggests that instead of using equation (1), it is more preferable to use (2):

$$|s| > 0{,}5\% \text{ and } |s+\Delta s| > 0{,}5\% \qquad (2)$$

where s, Δs take signed values. When s and Δs are same signed, no inadequate areas will be created, presuming obviously, a minimum longitudinal slope value.

The selection of longitudinal slopes along the vertical curve which obey to (1) or (2) does not offer adequate drainage. The same condition must be applied at the transition curves of the vertical alignment so as to ensure that none of the road's edge lines (as well as any other spot that lie on the pavement) and the rotation axis of the road have identical signs. In the same research [4] it is proved that the most adverse combination between s and Δs is when (3) is true:

$$s+\Delta s/2=0 \qquad (3)$$

where s, Δs as in (2).

On the present investigation, various values of the drainage gradient have been examined. The slopes are analytically calculated for the whole lane width and not just as a single oblique value per chainage (combination of longitudinal slope and superelevation). Several typical combinations of horizontal and vertical alignment are presented whilst illustrative examples point out the areas of bad drainage. Within the framework of the research the wheelbase of various types of motorcycles are compared with the length and the area of pavement portions with inadequate drainage.

II. ILLUSTRATION OF BAD DRAINAGE AREAS

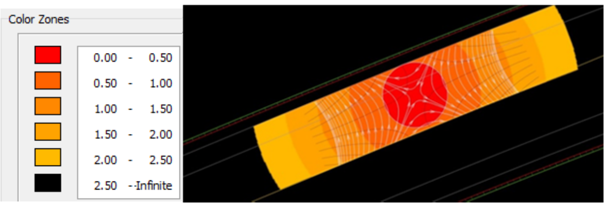
The determination of the path that the runoff takes along horizontal transition curves has been investigated by many researchers [7]-[10]. The adopted approach was to identify the resultant longitudinal and lateral slope in the vicinity of the transition curve which coincides with the flow of the water. On the present research the examination of ineffective drainage areas has been performed by exploiting sophisticated software, which allows the calculation and display of the resultant slope.

Aiming at the precise calculation of the flow lines, which indicate the path that the runoff takes to the pavement edge, a pattern curve was set. The attributes of the pattern curve are presented in Table I.

TABLE I
ATTRIBUTES OF PATTERN CURVE

Horizontal Radius	Transition curve length	Longitudinal slope	Cross slope Δs
200 m	50 m	-0.35%	0.70%
Tangent cross slope	Max. Superelevation	Total road length	Traveled way half-length (a)
-2.50%	7.50%	424 m	3.50 m

The contour lines of the pavement and the flow lines were also calculated through the same software. That was accomplished by converting the pavement as terrain in 1X1 meters grid and calculating the corresponding contours. The runoff paths, which are the perpendicular lines to the contour lines, were then drawn. The result of this process is illustrated on Fig. 1 (b) where there are also depicted the areas of resultant slope less than 0.5%. It is noted that from here onwards, the applied color gradation is the one determined in Fig. 1 (a).



(a) (b)

Fig. 1 Resultant slope color gradation (a), Final display (b) [11]

III. RESULTS

Within the present research framework, a number of different combinations of horizontal and vertical alignment models were created. These models, which are compared with the pattern curve (see Table I for attributes of the pattern curve) are oriented to present pavement sections with bad drainage areas.

According to (3) the worst scenario of bad drainage occurs when the longitudinal slope is equal to the half of the cross-slope invert (Fig. 2) where the center of the inadequate pavement drainage area is in the middle of the outer traffic lane and hence the pattern model was set with such features. In the rest of the models the values and sign of the longitudinal slope, the length of the horizontal transition curve and the direction of the curve are different compared to the pattern one. Various models are presented in Figs. 3-8 that were used to investigate a number of different combinations of horizontal and vertical alignments. By comparing the said models with the pattern one, crucial conclusions were drawn regarding the conditions which either favor or prevent inadequate water runoff.

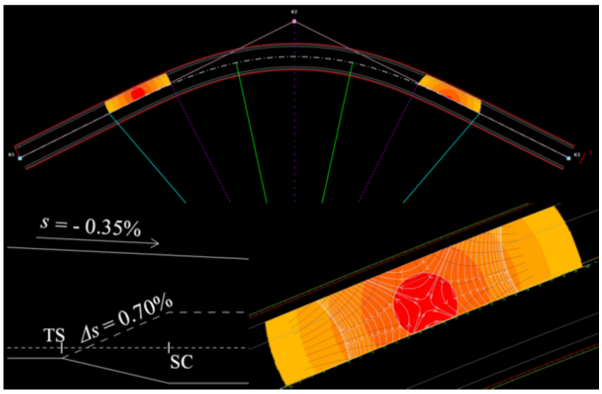


Fig. 2 Pattern model: Design and illustration of bad drainage area in the middle of the outer traffic lane [11]

A. Investigation in Relation to the Longitudinal Slope

Fig. 3 illustrates two road segments which are identical to the pattern one except for the fact that the upper one's longitudinal slope is increased in absolute terms from -0.35% to -0.55% whereas the lower one's longitudinal slope is decreased in absolute terms from -0.35% to -0.15%. In the inner area of the red circle and its concentric, the behavior of water runoff does not differ considerably among the three road segments. Outside the area of inadequate runoff, the flow of the water in all three cases is similar. The difference rests in the lateral displacement of the center of the concentric circles due to the variation of the longitudinal slope. In the pattern model the center of the circles is in the middle of the outer traffic lane whereas in the model with increased longitudinal slope, the center is shifted towards the outside edge of the traveled way. Finally, in the third model the center of the circle is shifted towards the axis of rotation.

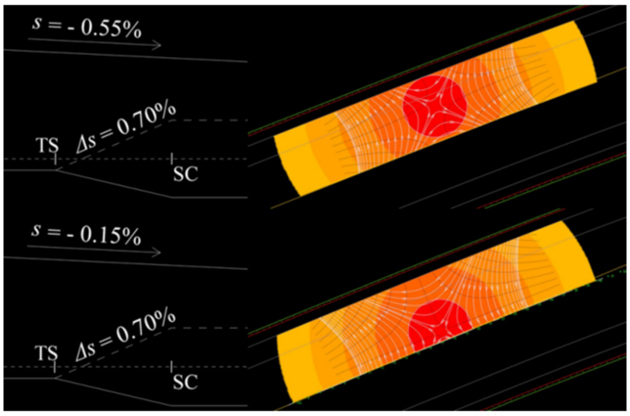


Fig. 3 Increase (top) and decrease (bottom) of longitudinal slope [11]

B. Investigation in Relation to the Length of the Horizontal Transition Curve

Fig. 4 presents a road segment, which has the double length of horizontal transition curve, compared to the pattern one. Previous researchers deduced that as the length of the transition curve reduces the water drains the pavement properly [12]. On the contrary, the elongation of the horizontal transition curve causes the decrease of the superelevation change rate in half and the proportional decrease of Δs (since the width of the traveled way a is the same). Due to the applied longitudinal slope the center of the inadequate runoff area is not in the middle of the outer traffic lane. In this case the diameter of the cyclic structures built is significant bigger, almost double and hence the area of inadequate runoff is larger.

As mentioned in a previous research [4], the Centre (Xc,Yc) and radius (r_{ab}) of the said cyclic structure in correlation to the full superelevation (q), normal crown (q_0), longitudinal slope (s_0), length of the transition curve (L) and the ultimate limit of the resultant gradient (ρ_0=0.5%) [6] are given by:

$$(Xc, Yc) = \left(\frac{q_0}{\frac{q+q_0}{L}}, -\frac{s_0}{\frac{q+q_0}{L}} \right) \tag{4}$$

$$r_{ab} = \frac{\rho_0}{\frac{q+q_0}{L}} \tag{5}$$

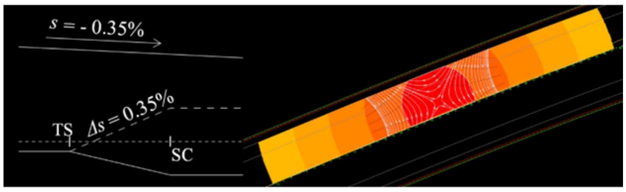


Fig. 4 Increased length of horizontal transition curve [11]

C. Investigation in Relation to Variable Longitudinal Slope

The model presented in Fig. 5 is the same as the pattern one with only difference the varied longitudinal slope within the horizontal transition curve.

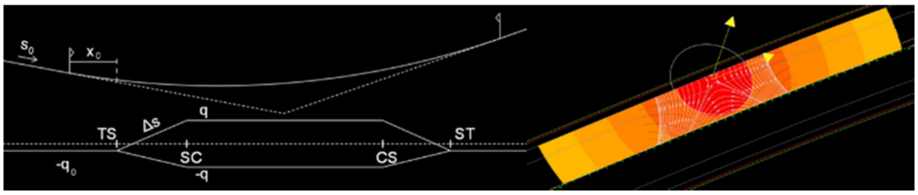


Fig. 5 Varied longitudinal slope [11]

The main dissimilarity is identified at the shape/structure of the inadequate runoff area. Relevant research [4] mentions that when the longitudinal slope is stable, cyclic structures are formed whereas when the slope varies, the structures become elliptic. Therefore, in the present case the boundaries of the area with relative gradient lower than 0.5% are determined by an ellipse. In the same research it is inferred that the radius and area of the portion of the pavement where the water will not runoff properly, are virtually the same as if the road had constant longitudinal slope and hence (4) and (5) are also applicable in this case.

D. Investigation in Relation to the Sign of the Longitudinal Slope

In Fig. 6 the sign of the longitudinal slope is the same as in the superelevation transition slope whereas the rest of the attributes are are similar to the pattern model. It is apparent that the area of inadequate runoff is declined almost to zero since only a minor portion of the red circle is still visible. Note that assuming longitudinal slope s equal to 0.5%, the red circle would be totally vanished. However, this combination of horizontal and vertical alignment would not be acceptable according to (1) while on the contrary it is acceptable according to (2).

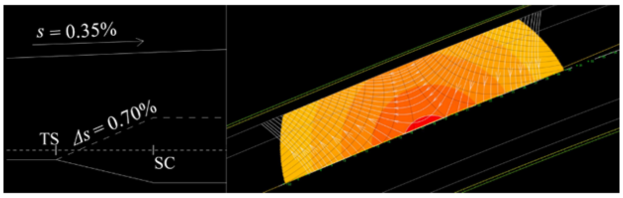


Fig. 6 Reverse sign of longitudinal slope [11]

E. Investigation in Relation to the Direction of the Curve

In all the previous models the direction of the horizontal curve is right hand. Fig. 7 illustrates a left-hand curve model whereas all the other attributes are alike to the pattern one.

The investigation of such model with the pattern one results in two perfectly symmetrical shapes about the axis of rotation which coincides with the axis of the road. Therefore, the magnitude of the inadequate runoff area is not dependent with the direction of the curve.

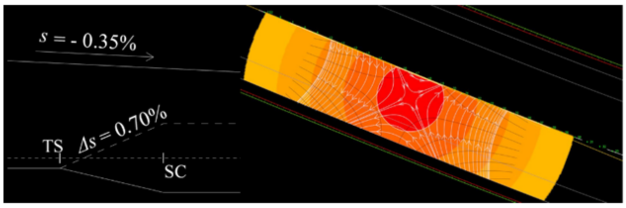
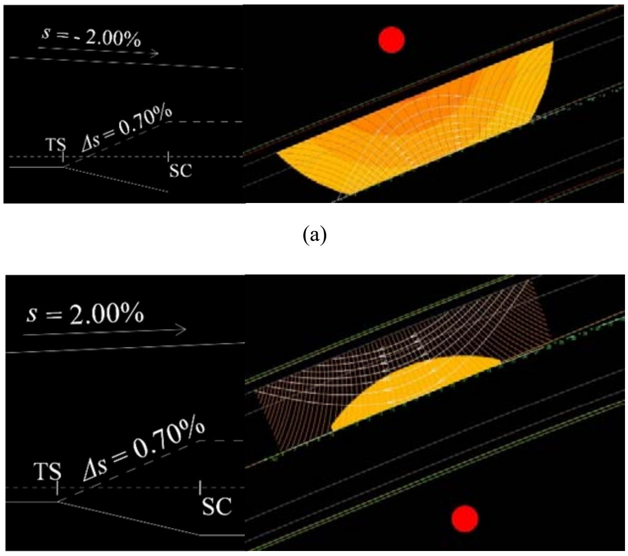


Fig. 7 Left hand horizontal curve [11]

F. Investigation in Case of Great Longitudinal Slope

Fig. 8 illustrates two road segments, which are identical to the pattern one with the exception of the longitudinal slope value. More specifically the upper one's longitudinal slope is -2.00% (sign - stands for downgrade) while the lower one's +2.00% (sign + stands for upgrade). It is obvious that the center of the area which gradient slope is less than 0.5% lies out of the pavement on the side of the outer traffic lane on the upper road segment whereas on the lower one the corresponding point is also located out of the traffic lanes but on this occasion it lies on the side of the inner traffic lane.



(a)

(b)

Fig. 8 Large longitudinal slope opposite to Δs (a) and like Δs (b) [11]

IV. Aggregate Results

According to the preceded investigation, the diameter of the portion of the pavement which will not provide adequate resultant slope in order to properly drain the rain water, for the various combinations of vertical and horizontal alignment included in Chapters A-F, can be calculated using (4). The results of these calculations are presented in Table II. As implied before (see (4)) the radius of the problematic area is not dependent on the sign or magnitude of the longitudinal slope.

TABLE II
Radius and Area of Problematic Areas

Investigation No	**q (%)**	**q_0 (%)**	**s_0 (%)**	**L (m)**	**ρ_0 (%)**	**Diameter of circle with slope less than 0.50% (m)**
1	7.50	2.50	-0.350	50	0.50	5,00
2	7.50	2.50	-0.550	50	0.50	5,00
3	7.50	2.50	-0.150	50	0.50	5,00
4	7.50	2.50	-0.175	100	0.50	10,00
5	7.50	2.50	0.350	50	0.50	5,00
6	7.50	2.50	-2.000	50	0.50	5,00
7	7.50	2.50	2.000	50	0.50	5,00

V. Motorcycle Wheelbase

It is very well known that certain types of motorcycleS such as touring and cruisers have longer wheelbases compared to sport bikes which are manufactured with substantially shorter wheelbase. The reason behind this characteristic is that motorcycles with longer wheelbases are more stable in straight road segments, while those with shorter ones are more responsive to tasks that demand rapid steering. Therefore, sport bikes, not only will stay longer in an area where water cannot run off properly due to their short wheelbase, but they will also travel faster and lean more than any other type of motorcycle and thus their safety level will be deteriorated.

Table III presents the wheelbase for the top 5 models sold in the EU for 2013 [13] according to the technical specifications of the motorcycle manufacturers.

TABLE III
Wheelbase of top 5 Motorcycle Models Sold in EU in 2013

No	Brand	Model	Wheelbase (m)
1	BMW	R1200GS	1.519
2	PEUGEOT	KISBEE 50	1.256
3	VESPA	LX 50	1.280
4	YAMAHA	XMAX 125	1.525
5	YAMAHA	XP500 TMAX (530cc)	1.580

By comparing the last columns of Tables II and III, it is clear that all of the motorcycles included in Table III will have both their wheels inside the problematic area for some time depending on their travel speed and trajectory. In the worst scenario of Tables II (case 4) and III (No 2), the motorcycle will have both of its wheels inside the problematic area for approximately 8 times as much as its wheelbase. That is particularly important because in this section the rider will have to lean his bike in an area where the water does not drain properly.

Apparently it is not implied that the motorcycle will hydroplane since hydroplaning depends on multiple factors (e.g. tire size, tire tread pattern, tire tread depth, tire pressure, water depth, water composition, vehicle speed, vehicle weight, road surfacing type) [1]. However even the slightest unexpected behavior of the motorcycle might have tremendous results on the control responses of the rider and hence the minimization of the area of inadequate water runoff, is vital.

VI. CONCLUSIONS

The investigation of water runoff on the road surface of a road segment is a crucial parameter in safety terms, since standing or pooling water on the pavement of a road might have severe consequences, e.g. hydroplaning. Several conclusions are drawn based on the preceded investigation of the models which combined various vertical and horizontal attributes of a road segment, that favor, prevent or do not affect at all, poor water runoff.

The variation of the longitudinal slope involves the vertical shift of the center of the poor water runoff cycloid area. This area is increased with the elongation of the length of the transition curve. The more the length of the transition curve the more area of poor water runoff is created. Moreover, the varied longitudinal slope along the horizontal transition curve converts the cycloid structure built of the poor water runoff area to an elliptic one whereas when the longitudinal slope and Δs of the outer edge line are similarly signed then the problem of inadequate water runoff is reduced.

Another conclusion drawn is that the presence of upgrade instead of downgrade vertical curve, between reverse longitudinal slopes, which edges coincide with the edges of the horizontal curve, implies the better water runoff whereas according to (1) and (2) the more the values of the longitudinal slope increases, regardless of its sign, the more poor water runoff areas are vanished from the pavement of the road. Lastly the direction of the horizontal curve has no impact to the form of the water runoff area.

Based on the preceded analysis it is clear that any kind of motorcycle will travel for some time inside the area of improper runoff for a certain time frame which depends on the speed and trajectory along the transition curve. Taking into account that this section is part of the transition curve where the rider will have to lean his motorcycle and hence reduce the contact area of his tire with the pavement it is obvious that any variations on the friction value due to the presence of a water film may lead to serious problems regarding rider’s safety. Therefore, efforts should be put in order to further investigate the conditions under which water effectively drains out of the pavement.

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REFERENCES

[1] D. B. C. &. D. Allopi, "Re-evaluating superelevation in relation to drainage requirements and vehicle dynamics" vol. 128, no. ISSN 1743-3509, 2012.

[2] N. Eliou and G. Kaliabetsos, "Investigation of rain water runoff problem in critical sections of road design" in 3rd Pan-Hellenic Highway Engineering Conference -Technical Chamber of Greece, Athens, 2012.

[3] T. Alimonakis, "Investigation of rain water runoff from crucial areas of the pavement", Bachelor Thesis - University of Thessaly - Department of Civil Engineering, Volos, 2018.

[4] G. Kaliabetsos, "Development and optimization of algorithms for the design of transport projects", PhD Thesis - University of Thessaly - Department of Civil Engineering, Volos, 2017.

[5] Greek Ministry of Environment, National Road Design Guidelines Manual Chapter 3: Alignments (ΟΜΟΕ - Χ), ΥΠΕΧΩΔΕ ΓΓΔΕ/ΔΜΕΟ, 2001.

[6] American Association of State Highway and Transportation Officials, "A Policy on Geometric Design of Highways and Streets", AASHTO, Washington, DC 20001, ISBN: 978-1-56051-508-1, 2011.

[7] A. S. Forschungsgesellschaft für Straßen- und Verkehrswesen, Kommentar zu den Richtlinien für die Anlage von Landstrassen (RAL-L1).: Linienführung, Arbeitsgruppe Strassenentwurf, 1979.

[8] I. D. Kofitsas, "Στοιχεία Οδοποιίας", Αθήνα: Ίων, ISBN: 9789604111855, 1997.

[9] B. Psarianos, Highway Engineering I - Super Elevation Diagrams, Athens: National Technical University of Athens - School of Rural and Surveying Engineering - Laboratory of Transportation Engineering.

[10] O. Guven and J. G. Melville, "Pavement Cross Slope Design - A Technical Review" Auburn University - Highway Research Center, 238 Harbert Engineering Center - Auburn, AL 36849-5337, 1999.

[11] http://www.anadelta.com/index-gr.php?s=tessera. [Online]. [Accessed 09 11 2018].

[12] R. Lamm, B. Psarianos and T. Mailander, "Highway Design and Traffic Safety Engineering Handbook", New York: McGraw-Hill Companies Inc., ISBN: 0070382956, 1999.

[13] ACEM, "2013 Statistical overview," ACEM, Version 24.01.14, 2014.