Pavement Grooving Pattern Direction Investigation as a Countermeasure of Hydroplaning

Konstantinos Apostoleris, Phd Candidate
National Technical University of Athens, Athens, Greece, GR-15773
School of Rural and Surveying Engineering
Department of Infrastructure and Rural Development
Email: kapostol@central.ntua.gr

Basil Psarianos, Professor
National Technical University of Athens, Athens, Greece, GR-15773
School of Rural and Surveying Engineering
Department of Infrastructure and Rural Development
Email: bpsarian@mail.ntua.gr

Vassilios Matragos, Phd Candidate
National Technical University of Athens, Athens, Greece, GR-15773
School of Civil Engineering
Department of Transportation Planning and Engineering
Email: vasmatragos@mail.ntua.gr

Stergios Mavromatis, Assistant Professor
National Technical University of Athens, Athens, Greece, GR-15773
School of Civil Engineering
Department of Transportation Planning and Engineering
Email: stemavro@central.ntua.gr

Kiriakos Amiridis, PhD
National Technical University of Athens, Athens, Greece, GR-15773
School of Rural and Surveying Engineering
Department of Infrastructure and Rural Development
Email: kyriakos.amiridis@gmail.com

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ABSTRACT

Pavement grooving has been proven to be an efficient pavement constructional mitigation measure to address hydroplaning phenomena, especially in freeways. However, this technique is associated with high noise levels when driving over a transversal grooving pattern, whereas stability issues arise over longitudinal grooving patterns for motorcyclists. The majority of grooving patterns, worldwide, are either transversal or longitudinal and only a limited number of diagonal grooving has been implemented in some, hydroplaning prone, freeway sections in the European Union (E.U) with promising results. This diagonal grooving pattern was initially based on an ad hoc engineering judgement without any systematic scientifically based investigation of the issue at the time.

The objective of this study is to compare the diagonal pattern with the transversal and longitudinal patterns: the transversal pattern is prone to generating high vehicle noise levels and reducing overall driving comfort, whereas the longitudinal pattern is prone to negatively affecting driving stability for motorcycles. Various diagonal pavement grooving patterns have been included in the present study via simulation scenarios in relation to the respective vehicle dynamics performance parameters. Specifically, the study aimed in finding an optimum angle value for safe vehicle accommodation over the diagonally grooved pavement section. Simulation scenarios have been used for every grooving pattern, i.e. longitudinal, transversal, and diagonal, in order to investigate the effect on longitudinal, lateral and vertical accelerations, vehicle roll, and pitch angles imposed on the vehicle and driver. Each pattern was evaluated for a broad range of relatively high speeds from 70 to 130 km/h, and for trucks and sport motorcycles. It is worth mentioning that three angle values were tested in the case of the diagonal grooving pattern: 30, 45, and 60 degrees.

The results show that the diagonal grooving pattern can, in fact, account for all the aforementioned deficiencies associated with the transversal and longitudinal patterns. Finally, the results of this study may provide a useful design and mitigation tool in terms of deciding the best grooving pattern to implement at a specific highway section.

Keywords: Pavement Grooving, Road Safety, Hydroplaning

INTRODUCTION

Hydroplaning represents one of the most critical road safety concerns that road designers have to account for (*1, 2, 3*). Hydroplaning of a vehicle occurs when a critical layer of water accumulates between the tires of a vehicle and the road surface, leading to a loss of traction and consequently to loss of control by the driver. Indicatively, it has been identified that hydroplaning on freeways is associated with:

- 17% of all crashes,
- 23% of all crashes on wet pavement,
- 28% of all skidding crashes on wet pavement,

whereas 15% of all hydroplaning cases is located on sections with superelevation rate change from positive to negative values and vice versa (*4*).

Crash analysis of vehicle control loss has shown that entering a curve generates a high potential for hydroplaning occurrence (*5, 6, 7, 8*). The frequency of hydroplaning phenomena in curves increases when the corresponding superelevation rate is less than the required minimum superelevation, approximately 0.5%, that offers adequate drainage sufficiency. If the corresponding longitudinal slope to the aforementioned curve does not result in an adequate compound slope for sufficient water drainage purposes, then the developed water film depth may become critical for hydroplaning occurrence. Ressel and Herrmann (*8*) have found that the crash risk at locations with these specific characteristics is five times higher at wet, as opposed to dry pavements.

Hydroplaning is a very complex phenomenon related to four main factors: (a) roadway (geometric design, pavement surface characteristics, inadequate roadside drainage facilities, etc.), (b) vehicle (tire tread wear, vehicle type, ratio of tire inflation pressure, etc.), (c) driver (speed, acceleration, steering, braking), and (d) weather (rainfall intensity and rainfall duration) (*7,8*). Internationally, the available applicable countermeasures for hydroplaning phenomena are nine (*7*):

1. Increase of superelevation rates on curves,
2. Increase of the roadway grade,
3. Adjustment of the required superelevation runoff length,
4. Implementation of negative superelevation rates equal to -2.5%, as in the case of tangent sections, on circular arcs for radii greater than 4000 m
5. Construction of porous asphalt,
6. Construction of radial surface gutters,
7. Construction of pavement grooving,
8. Implementation of skew superelevation runoff,
9. Imposition of proper posted speed limit.

From the above countermeasures, the concept of pavement grooving has been adopted in numerous highways worldwide, mainly on concrete pavements and especially in the US and Germany. The main disadvantage of longitudinal grooving is the “wiggle” (small lateral movements) that small vehicles and motorcycles may encounter while driven on grooved pavements. According to US standards (*9*), this problem can be mitigated by limiting the groove spacing to 20 mm and using 3 mm wide grooves, whereas German regulations recommend maximum longitudinal groove widths between 2.4 mm and 2.6 mm (*10*). As far as transversal grooving is concerned, the main disadvantage of this aspect is that vehicles generate high levels of tire-pavement noise when they pass over these grooved areas. Moreover, transverse joint opening widths negatively impact overall tire-pavement noise levels; the impact increases as the joint gets wider and deeper: a wide joint that is 1.25mm wide and 2.5mm deep can add between 1 and 1.5 dBA to the noise level generated from a pavement (*11*).

The introduction of pavement grooving on roadway surfaces considerably reduces the water film depth, mitigating the occurrence of wet weather accidents in critical areas (*12*). However, the efficiency of such grooves is reduced during winter in areas with very low temperatures because of the frost-defrost phenomenon. Nevertheless, it can be implemented at high risk areas for hydroplaning occurrence, as a means of monitoring driver behavior and traffic events evolution.

INVESTIGATION AIM

The objective of the present study is to examine the impact of different pavement grooving direction patterns, i.e. Longitudinal, Transversal, and Diagonal (Figure 1) on both concrete and asphalt roadway pavements. The analysis was conducted with respect to the passenger comfort and the road safety of trucks and motorcycles, whereas the different scenarios were analyzed by utilizing two simulation programs: TruckSim for trucks (Version 2008) and BikeSim for motorcycles (Version 2006). The longitudinal, lateral and vertical accelerations as well as the resulting roll angle and roll angular velocity of the vehicles were analyzed as parameters during the simulation process. It is emphasized that, because of the aforementioned disadvantages associated with the transversal and longitudinal pavement grooving techniques, research regarding the diagonal, hybrid pattern between the longitudinal and transversal types, pavement grooving pattern (Figures 1 & 2) has also been conducted in the literature and, thus, will be examined in the simulation scenarios.

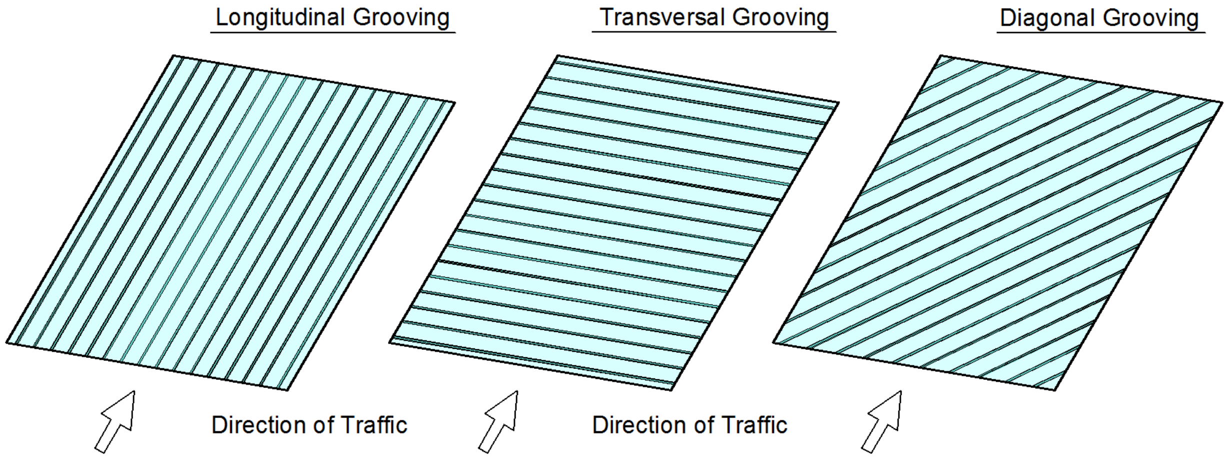

Figure 1 - Longitudinal, Transversal and Diagonal grooving patterns.

The geometrical characteristics of pavement grooving varies depending on each country's specifications and regulations as well as the type of directional pattern applied. It is worth mentioning that in-depth research has not been conducted regarding the application of diagonal pavement grooving patterns and therefore neither specifications nor explicit threshold values are readily available in regulations for the diagonal grooving pattern. The three geometric elements that determine the grooving pattern type are the groove width, depth, and spacing (axis to axis):

Two different geometric shapes can be found in the literature, namely the orthogonal pattern and the trapezoidal pattern (Figure 2) (*13*).

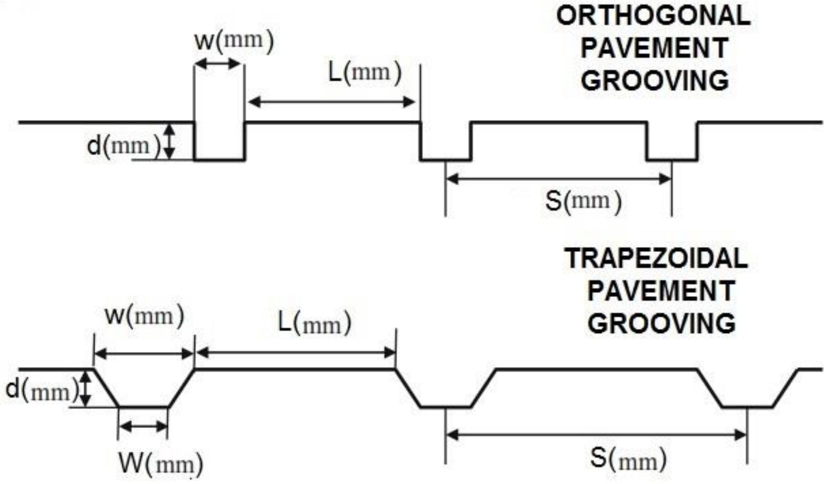

Figure 2 - Cross-section of grooving in orthogonal and trapezoidal pattern.

where, d (mm) = the depth of the pavement grooving
w (mm) = the width of the pavement grooving
W (mm) = the lower width of the pavement grooving on trapezoidal pattern
L (mm) = the distance between the edges of the grooves
S (mm) = the distance between grooves (axis to axis)

Because of the limitations associated with the TruckSim and BikeSim simulation platforms, only the trapezoidal, as opposed to the orthogonal, cross-section pattern has been utilized with the following geometrical characteristics:

- The depth of pavement grooving is considered 5mm
- The range of the upper width of the trapezoidal pavement grooving is considered 3 to 7mm
- The range of the lower width of the trapezoidal pavement grooving is considered 1 to 5mm (1mm lower that the upper width in each side)
- Grooves spacing is considered 50mm.
- The road length with grooving pattern applied is assumed to be 25 meters.

ANALYSIS AND RESULTS

According to the geometrical elements and parameters mentioned in the preceding paragraph, 3d-Models of the road surface were created in order to be incorporated in the simulation software programs. It is noted that the 3d-Model in the cases of transversal and longitudinal grooving patterns were created for a straight section of the road and inputted in the two simulation software programs. As far as the diagonal patterns are concerned, the 3d-Model was created with high precision; however, the 3-d Model was inputted into the TruckSim and BikeSim simulation platforms with reduced accuracy due to the inability of these versions to process the best 3d-Model. It is emphasized that the latter fact, may affect the accuracy of the results in the three cases of the diagonal grooving patterns.

In the TruckSim software a standard truck was used, whereas in the BikeSim software a sport motorcycle was selected because smaller-sized motorcycles are not able to be processed in the simulation analysis in this particular simulation software.; these simulation vehicles are shown in Figure 3. In the simulation process, the different scenarios were set as follows: five grooving widths of 3, 4, 5, 6 and 7mm, speeds between 70 and 110km/h for trucks and speeds between 80 and 130km/h for motorcycles; in all cases the grooving depth was set equal to 5mm. In addition, it is noted that five different pavement grooving patterns were investigated (Figure 4): transversal and longitudinal patterns, forming 0 and 90 degrees respectively, and three different types of diagonal patterns forming 30, 45 and 60 degrees.

Figure 3 - Conventional Truck (TruckSim) and Sport Motorcycle (BikeSim) used in the simulation scenarios.

The results derived from the two simulation software programs concerns the acceleration experienced by the drivers and passengers (longitudinal Gx, lateral Gy, vertical Gy), as well as the relative roll angle and the angular rate. It is noted that in all cases, the change in vehicle speed did not practically affect the results, i.e. relative roll angle and angular rate, under study. Similar results were obtained for all parameters and for all speeds tested: from 70 to 110 km/h for the standard truck and from 80 to 130 km/h for the sport motorcycle. Therefore, the mean values of the output results were computed for all vehicle speeds tested, in relation to the width of the grooves applied, and are presented in Table 1.

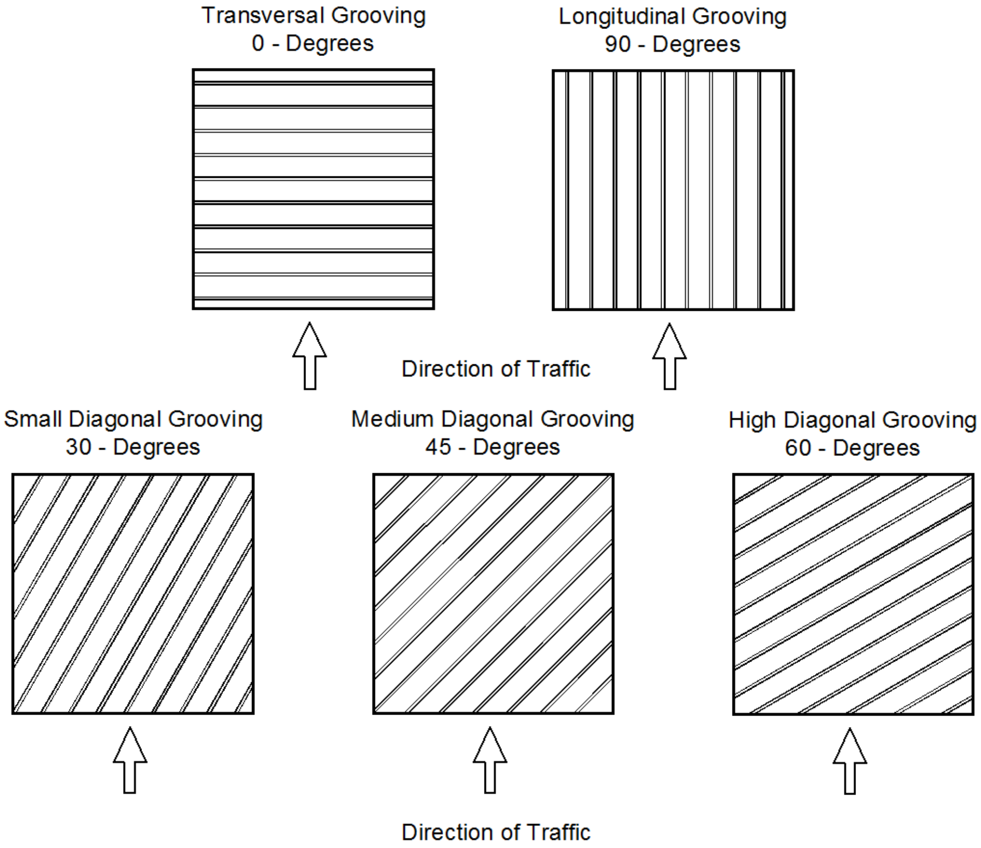

Figure 4 - Grooving patterns examined.

TABLE 1: Average Results from TruckSim and BikeSim for all Parameters in Relation to the Grooving Width and the Pattern Angle.

	TruckSim Output (Average results for velocity between 70 and 110 km/h)					**BikeSim Output (Average results for velocity between 80 and 130 km/h)**				
Grooving Pattern Angle (degrees)	**Grooving width (mm)**					**Grooving width (mm)**				
	3	**4**	**5**	**6**	**7**	**3**	**4**	**5**	**6**	**7**
	Relative roll angle (degrees)					**Relative roll angle (degrees)**				
0	0.085	0.116	0.097	0.088	0.112	1.674	1.743	1.601	1.619	1.647
30	0.269	0.219	0.247	0.290	0.333	1.719	1.717	1.712	1.716	1.731
45	0.260	0.259	0.237	0.191	0.226	1.687	1.694	1.702	1.731	1.747
60	0.255	0.255	0.235	0.269	0.263	1.723	1.745	1.726	1.785	1.975
90	0.123	0.175	0.161	0.241	0.308	1.822	1.848	2.010	2.381	2.272
	Angular Rate (degrees/sec)					**Angular Rate (degrees/s)**				
0	0.645	0.679	0.649	0.666	0.661	2.234	2.665	2.488	3.632	3.560
30	3.495	3.652	3.833	2.931	3.044	7.594	7.178	8.022	8.259	9.270
45	3.711	3.152	3.380	2.426	3.406	5.389	7.129	7.743	10.191	10.056
60	3.996	3.816	4.148	3.534	3.972	5.885	6.340	11.072	14.832	18.762
90	2.535	2.302	2.890	2.717	3.631	8.572	13.610	22.782	25.927	33.470
	Longitudinal Acceleration Gz (m/s^2)					**Longitudinal Acceleration Gz (m/s^2)**				
0	9.560	8.052	7.686	7.990	7.862	2.566	2.265	2.072	2.394	2.340
30	7.229	7.310	7.300	7.291	6.673	7.495	6.753	7.796	7.871	6.149
45	6.712	7.326	6.572	6.204	6.145	6.869	6.423	5.781	7.305	8.919
60	6.711	5.548	6.074	5.237	4.482	5.001	5.463	6.409	6.924	7.283
90	0.734	0.754	0.735	0.874	1.064	7.020	7.534	6.775	6.183	8.089
	Lateral Acceleration Gy (m/s^2)					**Lateral Acceleration Gy (m/s^2)**				
0	1.938	1.601	1.809	1.546	1.720	0.000	0.000	0.000	0.000	0.000
30	8.982	7.615	6.127	7.342	4.806	0.340	0.362	0.293	0.350	0.344
45	10.826	10.149	9.368	8.461	7.220	0.296	0.315	0.303	0.296	0.438
60	9.960	9.200	8.221	7.595	6.848	0.291	0.245	0.659	0.782	0.811
90	7.556	6.354	5.254	4.448	3.867	1.975	2.935	3.280	2.762	2.845
	Vertical Acceleration Gz (m/s^2)					**Vertical Acceleration Gz (m/s^2)**				
0	1.117	1.094	1.520	1.279	1.303	2.144	2.184	2.430	2.141	2.087
30	2.026	2.341	2.180	2.369	2.577	2.991	3.208	3.745	3.802	4.153
45	1.471	1.829	2.027	2.359	2.179	2.782	2.892	2.848	3.472	3.031
60	1.288	1.749	1.660	1.921	1.850	3.496	2.856	4.244	4.001	5.700
90	1.523	1.026	1.163	1.311	1.313	5.228	7.272	6.737	7.183	5.526

By observing the values presented in Table 1, it is evident that almost all examined parameters are not practically affected by the applied grooving width. The only exception is the angular rate parameter in the case of sport motorcycles, in which for a grooving width of 3mm in the longitudinal grooving pattern, the results pertaining to the angular rate are about 75% lower than the respective results corresponding to a 7mm grooving width. Similar results are also obtained in the case of the 60 degrees diagonal grooving pattern in which the angular rate regarding sport motorcycles decreases by approximately 65% when the grooving width changes from the 7mm to 3mm;for the 45 degrees diagonal pattern, the respective decrease of the sport motorcycle angular rate is around 45%. These findings confirm the necessity of applying very small grooving widths in the longitudinal grooving pattern cases; a practice that has already been proposed in the literature: according to US regulations, a parallel grooving width of 3mm is suggested for the longitudinal grooving pattern, whereas in the German regulations this parallel grooving width is reduced to the range between 2.4 and 2.6mm. Therefore, based on the results of this present analysis, it is confirmed that the above limiting values regarding the parallel grooving width are critical and in favor of motorcycle safety.

In relation to the results presented in Table 1, it is noted that the values of the longitudinal and lateral acceleration in the case of a typical single unit truck driving over a grooving pattern are particularly high, a fact that significantly reduces the comfort that drivers and passengers experience while passing over the grooving pattern. The high values presented in the longitudinal acceleration for the transversal grooving pattern might explain the high noise levels produced by these grooving patterns when vehicles pass over them. In summary, the range of values for every parameter examined is described below:

- The values regarding the angle roll range between 0.085 and 0.333 degrees for a truck passing vehicle, whereas for motorcycles these values range between 1.601 and 2.272 degrees. These results are similar to the common values expected to be generated by vehicles under normal driving conditions.
- The values regarding the angular velocity rate range between 0.645 and 4.148 degrees/s for trucks, whereas for motorcycles these values range between 2.234 and 33.47 degrees. The results obtained for trucks are similar to the common values expected from vehicles when grooving patterns are not present, but some values obtained for motorcycles are relatively high.
- The values of the longitudinal acceleration range between 0.734 and 9.56 m/sec^2 for trucks, whereas for motorcycles the longitudinal acceleration ranges between 2.072 and 8.089 m/s^2. Longitudinal acceleration values greater than 3.0 m/s^2 are not common in roads with high speed limits.
- The values of the lateral acceleration range between 1.546 and 10.826m/s^2 for trucks, whereas for motorcycles the lateral acceleration ranges between 0.000 and 2.845 m/s^2. The results obtained for motorcycles are similar to the common values expected from vehicles, whereas for trucks values greater than 3.0 m/s^2 are not, in general, typical.
- The values of the vertical acceleration range between 1.094 and 2.577 m/s2 for trucks, whereas for motorcycles the vertical acceleration ranges between 2.141 and 7.183 m/s2. The results obtained for motorcycles are similar to the common values expected from the drivers, whereas for trucks values greater than 3.0 m/s2 are not, in general, typical. According to the results in Table 1, and taking into account that the parameters in relation to the grooving width remain the same, Table 2 presents the average values for all parameters, in relation to the grooving pattern applied. From these results, it can be seen that the transversal grooving pattern is the most favorable choice over the other four pattern combinations, either diagonal or longitudinal. It should be noted, however, that for the three diagonal patterns examined, the results of all parameters were expected to range between the values obtained from the transversal and the longitudinal pattern. This was not confirmed for the three out of five parameters examined, a finding which may be due to the inability to import the grooving 3d-Model with high accuracy information in both software simulation platforms. Therefore, these results should be evaluated with some caution.

Additionally, the diagonal, compared to the longitudinal, grooving pattern appears to generate significantly better traffic conditions, in terms of comfort and safety, for the case of the sport motorcycles. This statement is justified by the fact that the values of all the vehicle dynamics parameters that were examined have been reduced; in fact, the values for three of them, i.e. angular rate, longitudinal and vertical acceleration, have been reduced by at least 50%. In this context, further consideration should be placed on the application of some diagonal grooving patterns in terms of testing whether they produce less noise levels compared to the transversal pattern. In addition, the increase in driver's comfort for sport motorcycle riders, in relation to the longitudinal grooving pattern, should be examined.

TABLE 2: Average Results from TruckSim and BikeSim for all Parameters in Relation to the Pattern Angle.

TruckSim Outcome (Average results for velocity between 70 to 110 km/h)					
Grooving Pattern Angle (degrees)	**Relative roll angle (degrees)**	**Angular Rate (degrees / s)**	**Longitudinal Acceleration (m/s^2)**	**Lateral Acceleration (m/s^2)**	**Vertical Acceleration (m/s^2)**
0	0.100	0.660	8.230	1.723	1.263
30	0.272	3.391	7.160	6.974	2.299
45	0.235	3.215	6.592	9.205	1.973
60	0.256	3.893	5.611	8.365	1.693
90	0.202	2.815	0.832	5.496	1.267
BikeSim Outcome (Average results for velocity between 80 to 130 km/h)					
Grooving Pattern Angle (degrees)	**Relative roll angle (degrees)**	**Angular Rate (degrees / s)**	**Longitudinal Acceleration (m/s^2)**	**Lateral Acceleration (m/s^2)**	**Vertical Acceleration (m/s^2)**
0	1.603	2.772	0.000	2.471	2.193
30	1.674	8.077	0.381	7.310	3.629
45	1.664	8.825	0.337	7.146	3.198
60	1.757	11.510	0.513	5.510	3.832
90	2.050	21.786	2.636	6.908	6.329

CONCLUSIONS

The purpose of this study was to examine the longitudinal and transversal grooving pattern applied worldwide according to the specifications, and to compare these longitudinal and transversal grooving patterns with the diagonal grooving pattern; the final outcome was to identify the pros and cons that each grooving pattern type presents. For this purpose, two simulation packages were utilized, one for trucks (TruckSim, 2008) and one for motorcycles (BikeSim, 2006): the reason that these specific vehicle types were examined is that the behavior of these vehicles is particularly critical in grooving areas. The following findings can be concluded from the analysis:

- From the five grooving patterns investigated, it appears that the transversal grooving pattern presents the most favorable traffic conditions in terms of comfort and safety for both trucks and motorcycles. It should be noted, however, that the transversal grooving pattern produces a high tire-pavement noise, a phenomenon which is significantly mitigated with the longitudinal grooving pattern. Similarly, this tire-pavement noise which is identified in the transversal grooving pattern case appears to be reduced by a considerable percentage in the diagonal grooving pattern case.

- The longitudinal grooving pattern raises important issues in terms of motorcycle driving stability and thus overall safety for the motorcycle riders; this issue appears in an even more evident manner in areas where the applied grooving width is greater than 3mm. For this reason, it is advised that the the longitudinal grooving pattern be constructed with a grooving width less than or equal to 3mm in order to ensure an increased level of road safety in roadway sections where a high percentage of motorcycles is present. It is noted that the diagonal grooving patterns, compared to longitudinal patterns, seem to increase motorcycle stability and therefore overall safety of motorcycle riders.
- The values found for the investigated parameters corresponding to the diagonal grooving pattern are particularly high. Regarding the results obtained from the TruckSim software it is observed that all values for all parameters, regarding the diagonal grooving pattern, were higher than the respective values corresponding to the longitudinal and transversal grooving pattern. It is emphasized that these results were not expected. On the other hand, the diagonal grooving pattern, as opposed to the longitudinal pattern, appears to offer significantly better comfort to the sport motorcycle rider. In four out of five parameters examined (relative roll angle, angular rate, longitudinal and vertical acceleration), the values corresponding to the application of the 45-degree grooving pattern, compared to the longitudinal grooving pattern, were reduced; more specifically the aforementioned reduction was at least 50% for three parameters, i.e. angular rate, longitudinal and vertical acceleration. Therefore, the diagonal grooving pattern may be considered to replace the longitudinal pattern in areas where increased motorcycle traffic is expected.

SUBJECT FOR FURTHER RESEARCH

Objects for further research could be the following:

- Conduct measurements with appropriate equipment regarding vehicle dynamics parameters on highway sections where the grooving method (especially for diagonal grooving pattern) has been implemented to validate the findings of this work.
- Examine more cases with different combinations of geometric elements and grooving characterictics: for example, the potential correlation between the grooving depth and groove spacing (axis to axis) in relation to traffic comfort and safety can be studied.
- Investigate the case of the orthogonal shape grooving. In the present study, only the trapezoidal pavement grooving type was analyzed due to the software limitations of TruckSim (2008) and BikeSim (2006) in terms of creating and analyzing the orthogonal grooving type.
- Investigate the effect of the diagonal grooving pattern compared to the transversal and longitudinal grooving pattern in terms of rainstorm drainage analysis and stimulating hydroplaning phenomena.
- Incorporate 3-d roadway surface models in a more robust and accurate manner in the simulation software platforms.
- Investigate the noise level of the diagonal grooving pattern in terms of testing whether they produce less noise levels compared to the transversal grooving pattern.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: B. Psarianos; data collection: K. Apostoleris, V. Matragos, K. Amiridis; analysis and interpretation of results: K. Apostoleris, V. Matragos, B. Psarianos; draft manuscript preparation: K. Apostoleris, B. Psarianos, S. Mavromatis, K. Amiridis. All authors reviewed the results and approved the final version of the manuscript.

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