6th International Symposium on HIGHWAY GEOMETRIC DESIGN

Pavement Grooving Pattern Direction Investigation as a Countermeasure for Hydroplaning

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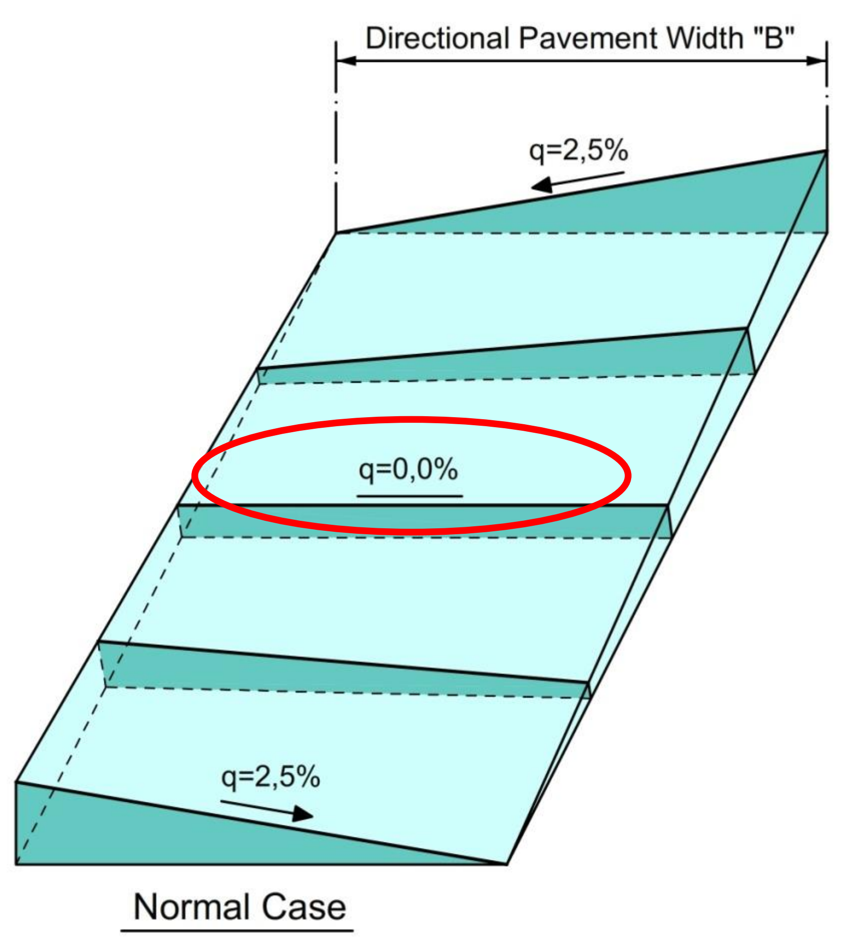
Objective of the Study

Pavement grooving has been proven to be an efficient pavement constructional mitigation measure to address hydroplaning phenomena, especially in freeways. The objective of this study is to compare the diagonal pattern with the transversal and longitudinal patterns considering that:

- transversal pattern is prone to generating high vehicle noise levels and reducing overall driving comfort while
- longitudinal pattern is prone to negatively affecting driving stability for motorcycles.

Various diagonal pavement grooving patterns were investigated 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, in order to investigate the effect on longitudinal, lateral and vertical accelerations, vehicle roll angle, and angular rate imposed on the vehicle and driver. Each pattern was evaluated for a broad range of relatively high speeds from 70 to 130 km/h for trucks and sport motorcycles. It is worth mentioning that three angle values were investigated in the case of the diagonal grooving pattern: 30, 45, and 60 degrees.

The hydroplaning problem



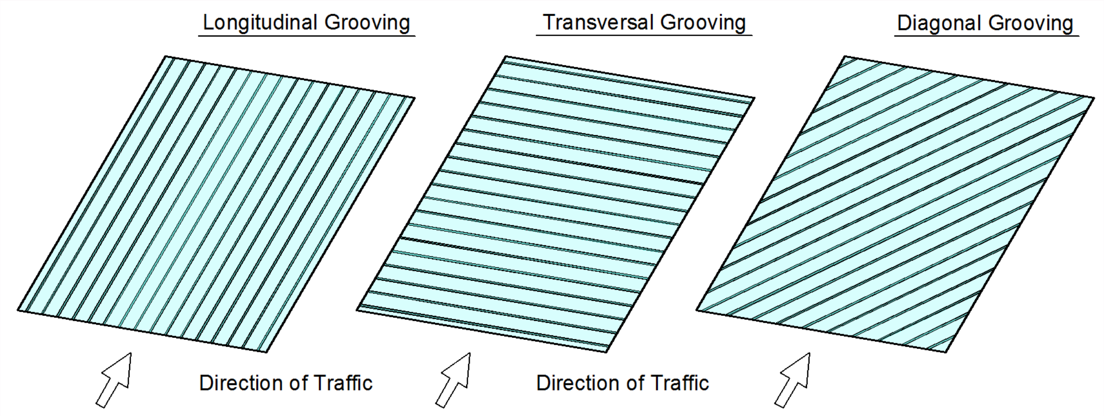
Hydroplaning represents one of the most critical road safety issues that road designers must solve. Hydroplaning of a vehicle occurs when a critical layer of water accumulates between the tires of a vehicle and the road surface, leading to a loss of traction and consequently to loss of control by the 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,

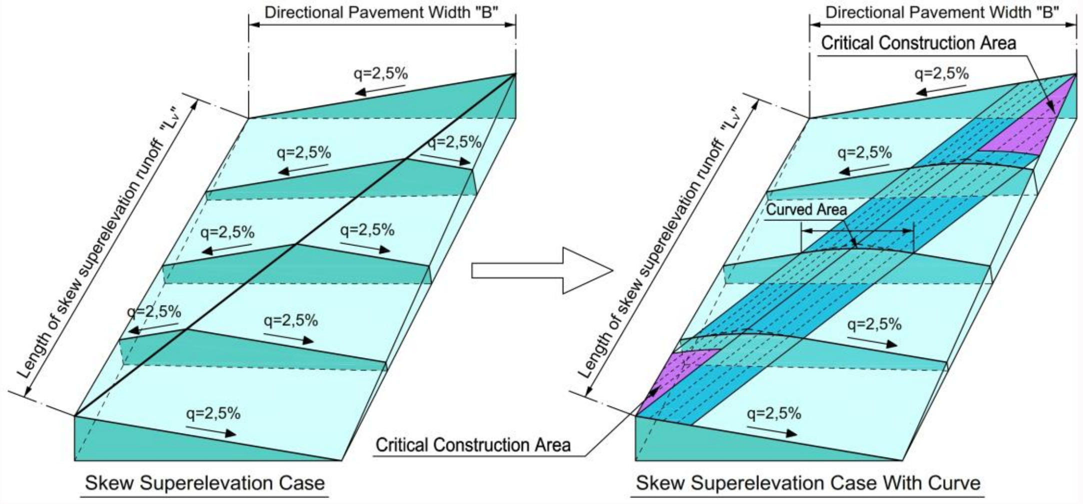
whereas 15% of all hydroplaning cases is located on sections with superelevation rate change from positive to negative values and vice versa

Techniques for counteracting the hydroplaning phenomenon

Construction of Pavement Grooving



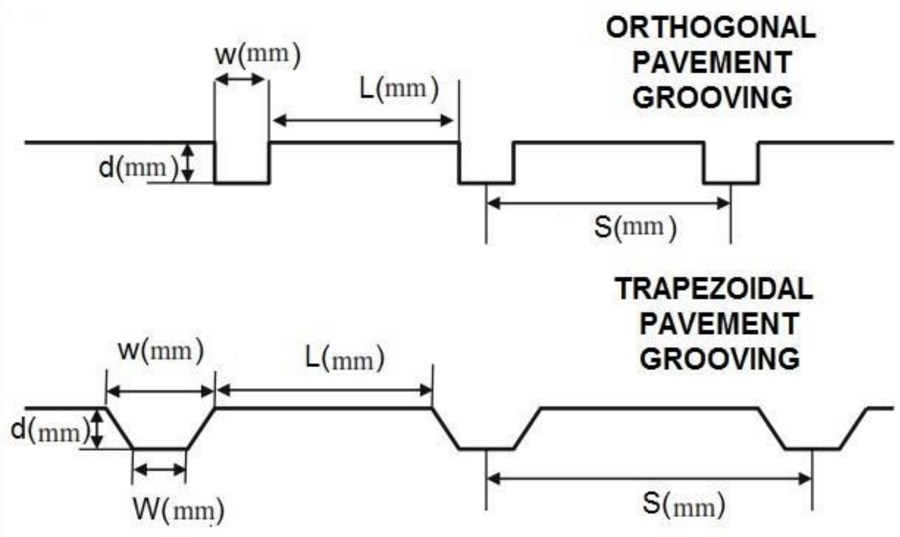
Skew Superelevation Runoff



Internationally, the available techniques for counteracting the hydroplaning issue are nine:

1. Increase of superelevation rates on curves,
2. Increase of roadway longitudinal slope,
3. Adjustment of the required superelevation runoff length,
4. Implementation of negative superelevation rates on circular arcs for radii greater than 4000 m and equal to the value of cross-slope of tangents (-2.5%) thus not having superelevation change,
5. Construction of porous asphalt,
6. Construction of radial surface gutters,
7. Construction of Pavement Grooving,
8. Construction of Skew Superelevation Runoff,
9. Proper posted speed (Reduced speed limit for raining conditions).

Construction of pavement grooving



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)

From these 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.

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.

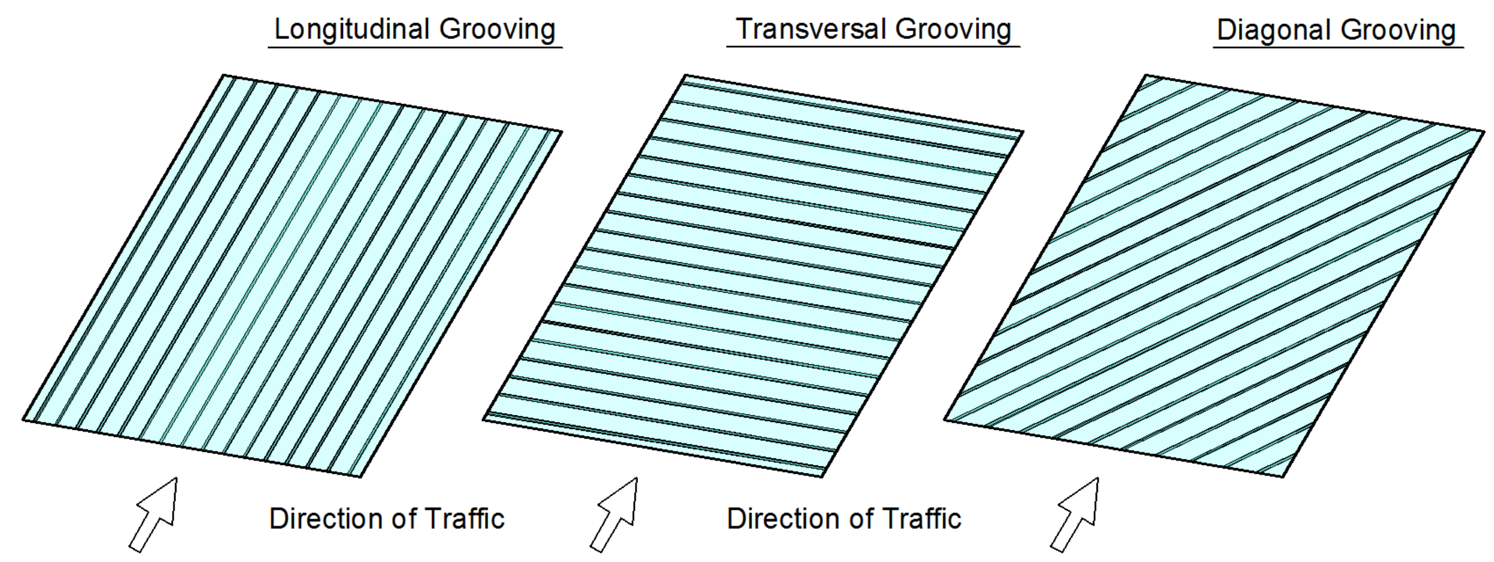
The introduction of pavement grooving on roadway surfaces considerably reduces the water film depth, mitigating the occurrence of wet weather accidents in critical areas. However, the efficiency of such grooves is reduced during winter in areas with very low temperatures because of the frost-defrost phenomenon.

Investigation Aim

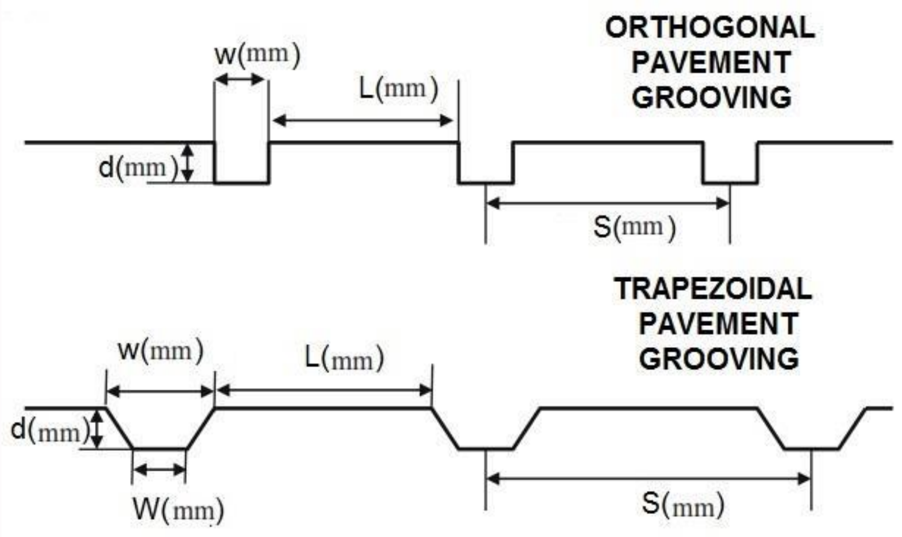
The objective of the present study is to examine the impact of different pavement grooving direction patterns (i.e. Longitudinal, Transversal, and Diagonal) on roadway pavements. The analysis was conducted in respect to the passenger comfort and the road safety of trucks and motorcycles, whereas the 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.



TruckSim – BikeSim Simulation



where,

d (mm) =	the depth of the pavement grooving
w (mm) =	the width of the pavement grooving
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L (mm) =	the distance between the edges of the grooves
S (mm) =	the distance between grooves (axis to axis)

Due to limitations associated with the TruckSim (2008) and BikeSim (2006) simulation platforms, only the trapezoidal pattern has been utilized with the following geometrical characteristics:

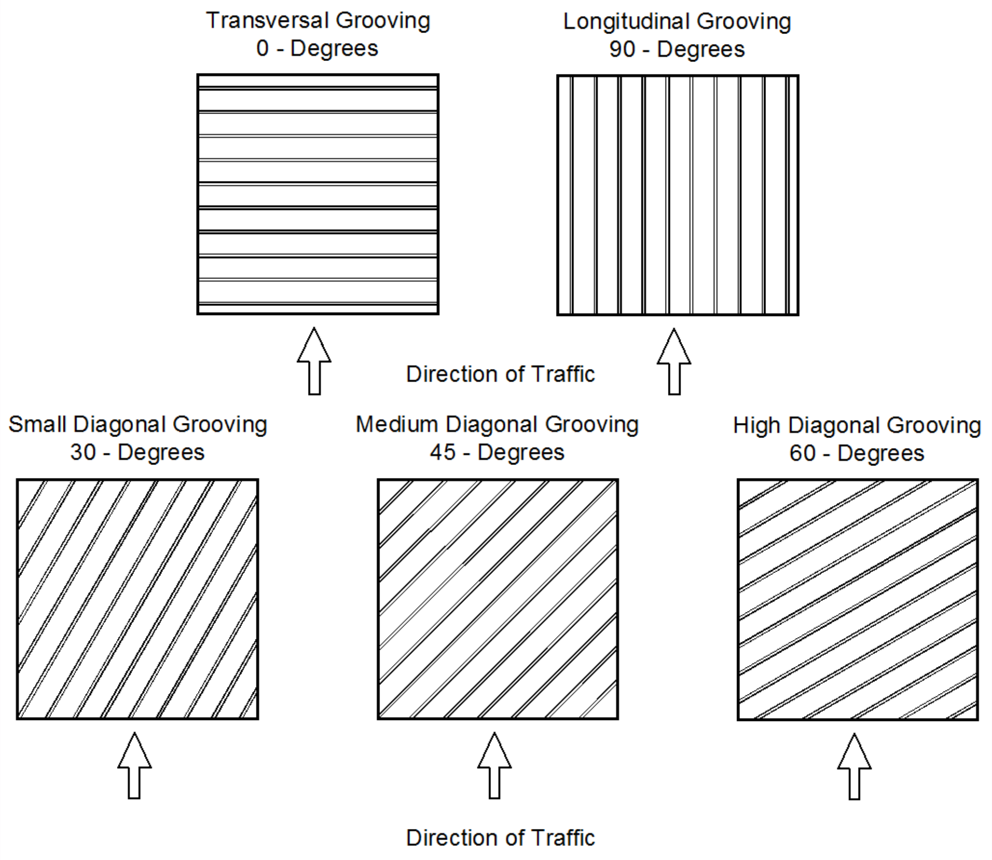
- The depth of pavement grooving is considered 5mm
- The range of the upper width of the trapezoidal pavement grooving is considered 3 to 7mm
- The range of the lower width of the trapezoidal pavement grooving is considered 1 to 5mm (1mm lower that the upper width in each side)
- Grooves spacing is considered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

TruckSim – BikeSim Simulation

According to the geometrical elements and parameters mentioned above, 3d-Models of the road surface were created for all cases in order to be incorporated in the simulation software programs.

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.

TruckSim – BikeSim Simulation



The results derived from the two simulation software programs concerns the acceleration experienced by the drivers and passengers (longitudinal Gx, lateral Gy, vertical Gz), as well as the relative roll angle and the angular rate of the vehicle.

Speed range between 70 and 110 km/h for a standard truck and from 80 to 130 km/h for a sport motorcycle were investigated. Similar results were obtained for all parameters and for all passing speed range.

Five different cases of pavement grooving were investigated:

- Transversal Grooving (0 degrees)
- Small Diagonal Grooving (30 degrees)
- Medium Diagonal Grooving (45 degrees)
- High Diagonal Grooving (60 degrees)
- Longitudinal Grooving (90 degrees)

TruckSim – BikeSim Outcome – Analytical Results

Grooving Pattern Angle (degrees)	TruckSim Output (Average results for velocity between 70 and 110 km/h) – Grooving width (mm) – Relative roll angle (degrees)					BikeSim Output (Average results for velocity between 80 and 130 km/h) – Grooving width (mm) – Relative roll angle (degrees)				
	3	4	5	6	7	3	4	5	6	7
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

Relative angle roll values are almost the same in all speed cases, in all grooving patterns for every grooving width, in both trucks and motorcycles.

TruckSim – BikeSim Outcome – Analytical Results

	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**
	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

Angular Rate values are much lower in transversal grooving pattern and almost the same in all speed cases for every grooving width. In longitudinal pattern, values are founded much higher for any other case for motorcycles and especially for 7mm grooving width are almost 10 times higher than the transversal grooving pattern.

TruckSim – BikeSim Outcome – Analytical Results

Grooving Pattern Angle (degrees)	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 width (mm)					Grooving width (mm)				
	3	4	5	6	7	3	4	5	6	7
	Longitudinal Acceleration Gx (m/s^2)					Longitudinal Acceleration Gx (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

Longitudinal acceleration values for trucks are much lower in longitudinal grooving pattern, while for motorcycles values are almost 10 times higher. 6 ~ 10 times higher are also the longitudinal acceleration values for all other cases (diagonal and transversal grooving pattern) for both trucks and motorcycles.

TruckSim – BikeSim Outcome – Analytical Results

Grooving Pattern Angle (degrees)	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 width (mm)					Grooving width (mm)				
	3	4	5	6	7	3	4	5	6	7
	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

Lateral acceleration values are much lower for transversal grooving pattern in both cases for trucks and motorcycles. Diagonal grooving patterns seems to have 4 ~ 5 times higher values for trucks, while for motorcycles the higher values founded in longitudinal grooving pattern.

TruckSim – BikeSim Outcome – Analytical Results

Grooving Pattern Angle (degrees)	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 width (mm)					Grooving width (mm)				
	3	4	5	6	7	3	4	5	6	7
	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

Vertical acceleration values are almost the same in all speed cases, in all grooving patterns for every grooving width, in trucks. In motorcycles the results seems to be slightly higher in diagonal and in longitudinal grooving patterns in respect to the transversal grooving pattern.

TruckSim – BikeSim Outcome – General Results

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/s²)**	**Lateral Acceleration (m/s²)**	**Vertical Acceleration (m/s²)**
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/s²)**	**Lateral Acceleration (m/s²)**	**Vertical Acceleration (m/s²)**
0	1.603	2.772	2.471	0.000	2.193
30	1.674	8.077	7.310	0.381	3.629
45	1.664	8.825	7.146	0.337	3.198
60	1.757	11.510	5.510	0.513	3.832
90	2.050	21.786	6.908	2.636	6.329

- Relative angle roll values are almost the same in all speed cases, in all grooving patterns for every grooving width, in both trucks and motorcycles.
- Lower values for angular rate is achieved for transversal grooving pattern, while for diagonal and longitudinal grooving pattern results are more than 5 times higher.
- Lower value for longitudinal acceleration is achieved in transversal grooving pattern for trucks and for longitudinal grooving pattern in motorcycles. In both cases the diagonal grooving pattern has very high values for longitudinal acceleration.
- Lower values for lateral acceleration is achieved for transversal grooving pattern, while for diagonal and longitudinal grooving pattern results are more than 5 ~ 8 times higher.
- Vertical acceleration values are almost the same in all speed cases, in all grooving patterns for every grooving width, in trucks. For motorcycles the transversal grooving pattern has the lower value.

Conclusions

1. From the five grooving patterns investigated, 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.
2. Longitudinal grooving pattern **raises important issues in terms of motorcycle driving stability** and thus overall safety for the motorcycle riders; this issue appears even more in areas where the applied grooving width is greater than 3mm. It is noted that the diagonal grooving patterns, compared to longitudinal patterns, seem to increase motorcycle stability and therefore overall safety of motorcycle riders.
3. 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). 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 the present 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).
- 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.
- 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.

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Thank You for your attention!