



HAL
open science

Weather condition effect on the road surface friction: A Preliminary assessment based on sensor data

Mezgeen Rasol, Franziska Schmidt, Silvia Ientile

► To cite this version:

Mezgeen Rasol, Franziska Schmidt, Silvia Ientile. Weather condition effect on the road surface friction: A Preliminary assessment based on sensor data. IALCCE2023, Politecnico di Milano, Jul 2023, Milan, Italy. 9 p. hal-04197450

HAL Id: hal-04197450

<https://univ-eiffel.hal.science/hal-04197450v1>

Submitted on 6 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Weather condition effect on the road surface friction: A Preliminary assessment based on sensor data

M. Rasol *, F. Schmidt, S. Ientile

Université Gustave Eiffel, MAST/EMGCU, 5 Boulevard Descartes, 77454 Marne-la-Vallée 5 cedex 2, France

* Corresponding author: mezgeen.rasol@univ-eiffel.fr

ABSTRACT: Changes in weather condition have a significant influence on the road surface friction. Extreme weather conditions are considered during heavy rains, and ice accumulation or snow-fall for the study of road surface. This could modify the road surface friction, a decrease of the road surface friction due to extreme wet condition, and increase car accident rates. Weather condition related factors usually are water film thickness due to the rain, ice accumulation and major temperatures (pavement, ambient and freezing). Better understanding of the weather condition changes on the road surface friction coefficient considering real-scale data monitoring system is essential to acclaim a reliable maintenance solution for road transport infrastructures. Long term data collection is a key factor for assess the relation between weather conditions, road surface friction coefficient. In the current research study, a preliminary assessment of weather condition influence on the road surface friction is elaborated for eighteen months considering data-driven from a novel intelligent road-based passive sensor. Results show that the most extreme weather conditions could impact road surface friction coefficient over time in road transportation system; mostly due to an increase of water film thickness and possibility of ice accumulation on the road surface. In conclusion different friction thresholds are elaborated for traffic management procedures, mainly 0.80 friction coefficient is considered the most stable and standard conditions, 0.60 acceptable, and 0.30 is an urgent condition.

1 INTRODUCTION

1.1 *Main Background Knowledge*

Road crashes are a major concern and significant problem for highway owners and operators. There are numerous factors involved in a road accident rate. Friction between tires and pavements is considered one of the factors that could have a partial role in increasing accident rates. Poor friction on the pavement surfaces leads to uncontrolled condition of the driving task, partially this could have an impact on the driver behaviour during the riding. In particular this could be even more dangerous in wet conditions. Friction coefficient is subjected to numerous influential factors, which can be commonly classified into five categories First, tire-related factors (rubber compound, tire properties, rubber tread design and condition, inflation pressure, and tire operation temperature) [1]–[7]. Second, the road pavement surface - interrelated factors (pavement type, mix design materials, microtexture and macrotexture, surface temperature and construction age of the pavement) [8-15]. Third, intervening-substance-related factors (quantity particulate matter, and oil contaminants). Fourth, driver behavior related factors (stopping sight distance, driver health condition, speed control and knowledge of the surface pavement friction) [8]–[10]. and, the fifth category is weather conditions factors which can influence the friction between vehicle tires and road surface pavement [14], [19-24].

The study of weather conditions influences on the friction force generated between tires and road surface pavement is a key to advance knowledge on the road surface in order to provide an appropriate solution for traffic management procedures. On the other hand, an appropriate traffic management procedure depends on the relation between the road surface friction and weather condition. Weather conditions have significant influence on the driving task considering both on the road surface pavement which directly affect the driving operation and the climate weather which is an important factor being able to modify the driving task in the road network system[18], [19]. Combination of both cases could make an impact to the roadway system and in extreme cases, temporary closing roads is recommended. Weather conditions affects can be from various weather changes factors such as ambient temperature, pavement temperature, ice temperature on the road surface during extreme winter condition [20]. On the other hand, under specific

conditions, changes in weather condition can produce ice layer, water film. This could need an action which is commonly considered to decrease ice possibility (%) on road surface by means of a de-icing salt procedure. However, de-icing salt action could also affect the road surface when the deterioration is already on the pavement, independently of pavement materials (cement concrete or asphalt). These factors are essential to advance the knowledge on road surface friction coefficient which can partially (directly or indirectly) be involved in the increase of the accident crashes.

A complete traffic management procedure requires an adequate friction coefficient of the road surface pavement based on a specific minimum friction coefficient in a specific region considering changes in weather conditions. A steady minimum required friction of the roadway surface is mandatory. For this reason, an advanced understanding of the weather conditions which can affect the steady level of the friction is crucial to avoid obstacles in driving task operation on roadway. Weather condition data collection is a challenging task for infrastructure assessors specifically in real-time monitoring, and continues data acquisition. Different studies on the influence of the weather condition on road surface and friction has been conducted. Mainly water film thickness and air temperature are considered [21]. In several studies a significant influence of the pavement temperature on friction is identified [22], [23]. In addition, mentioned research studies are based on data-driven from models or/and commonly used techniques such as Finite Element based models [12], [24]–[26]. Although, some researches present insignificant or low influence of temperature on road surface friction [22], [27]. Current methodologies are still in use for the purpose of the weather daily data collection on road pavements, a challenge is how accurate and efficient data are taken in term of daily data acquisition. In this study a novel weather sensor is applied to automatically monitoring big data in the daily form or monthly form related to weather changes and factors influencing road pavement surfaces.

In recent works, the use of intelligent road-based passive sensor is highly recommended due to the advantages of ability of big dataset storage, invasive technique, contactless, environmentally approachable and the real time automated data acquisition considering similar interval-time of adverse parameters.

1.2 Objectives and contribution

During the last decades various researches have been conducted by considering diverse techniques in order to define the effect of the weather conditions related parameters on road surface friction. This work focuses on a real case study of the eighteen months data-driven based on a commercially developed intelligent road-based passive sensor. Thus, weather data are collected considering time-interval and location of data acquisition station for current research case study. The **main objective** of this research study is to present preliminary findings and results of a medium-size number of monitoring data on a real-case roadway system, and link to the followings highlighted points:

- Main objective: To monitor the road surface related data including weather condition and Friction coefficient of road surface on the real scale site based on the data driven from ice sensor in long term database.
- Sub-objective: Decision making tool to support road owners for the purpose of the traffic management procedures. To check with the minimum thresholds.
- The main link between weather condition factors influence on the traffic management procedures and friction coefficient thresholds.

The **contribution of this work** to the current knowledge is to understand how the consideration of the weather-related parameters can influence the friction stability. In order to provide a safe and reliable traffic management system it is crucial that the future friction measurement models take into account weather parameters.

2 CASE STUDY AND DATA COLLECTION

Intelligent road-based passive sensor is one of the innovative technologies to monitor the meteorological factors in the traffic road pavements. This sensor is installed towards the vehicle moving direction.

Data acquired for this research work is conducted for the purpose of the enhancing the resilience of the road transport infrastructure in the framework of the European project called PANOPTIS; aimed at increasing the resilience of the road transport infrastructures and remaining in safer and robust conditions during unfavorable conditions [28-29]. Data are acquired for eighteen months (starting December 2019 until June 2021) using intelligent road-based passive sensor.

This case study is conducted in the Spanish on-site highway located in Guadalajara province which connects Madrid city to Barcelona city. The length of the highway is about 77.5 kms (See Figure 1) with four lanes (two each traffic direction). Weather condition in mentioned zone can be severe and long winter session (temperature is commonly decreasing by $\sim 3^{\circ}\text{C}$) and hot and dry summer session (temperature is commonly increase to $\sim 50^{\circ}\text{C}$). The selection of this case study is based on three main reasons:

- The importance of the A2 Highway between two main and largest Spanish cities (Madrid and Barcelona).
- Diverse weather conditions [29].
- Road transport infrastructure age, and current health condition concern to public.

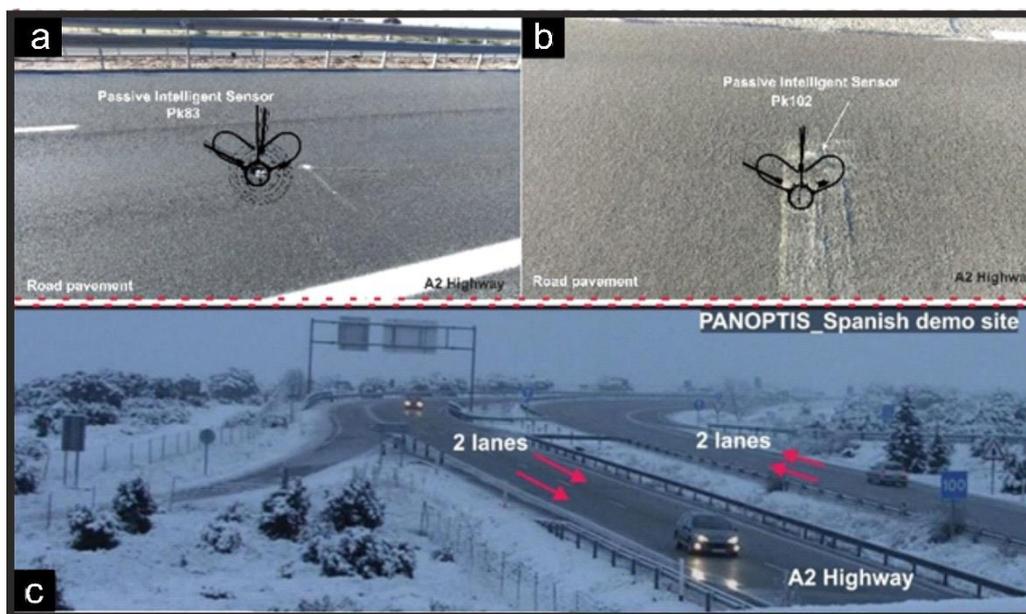


Figure 1. View of the case study in Spain; (a) Intelligent road-based passive sensor at station PK83, (c) Intelligent road-based passive sensor at station PK102, and (c) Spanish case study (adapted from previous work of authors [30]).

3 INFLUENCE OF WEATHER CONDITIONS ON ROAD SURFACE FRICTION

3.1 *The relation between road surface friction and weather-related parameters*

Safe highway pavement to serve a reliable transportation of humans and goods is crucial for further economy growth [13]. Understanding the pavement friction and factors affecting the operation of surface pavement texture is key in order to provide a safe, comfortable path for transportation operations. In this section, weather conditions factors are investigated by means of weather intelligent road-based passive sensor. Weather data are collected during eighteen months in a selected A2 highway case study in Spain (see section 2) for better understanding the influence of weather factors (e.g., ambient temperature, pavement temperature, ice temperature, ice possibility, water film thickness and road conditions) on pavement friction functionality and to further explore influence of each parameter individually on pavement friction. Various minimum thresholds are considered in the literature for a safe friction coefficient operation in road pavements [30]. Generally, a safe and optimal standard friction coefficient is considered in a range of 0.80 in normal conditions [31], and these range is also considered by Spanish authorities in this case study. Figure 3 presents the influence of (ambient or (in another meaning is air temperature and

pavement temperature) on the pavement friction. Ambient temperature alone could have slight influence on the friction of the road surface as shown a group of measurements in the square, which friction keeps in a normal range. In addition, during winter season with a decrease in ambient temperature in-between (0 - 10 °C), pavement friction decreases up to 0.58 according to the data collected in this case study this could be not only because of the ambient temperature but interaction with other weather condition for example the presence of temperature of ice layer/ice temperature or water on the road surface (see Figure 2. a and Figure 3. a and b). On the other hand, Figure 3. b presents a similar reduction in pavement friction during winter season when pavement temperature reaches a low range of (0 - 10 °C) This could be also partially related to the possibility of ice and rainfalls due to the accumulation of water on road surface.

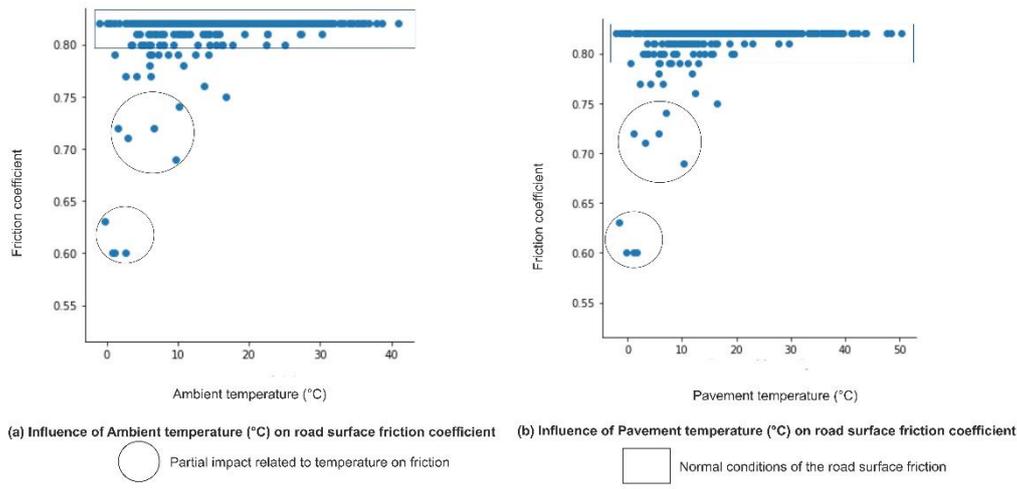


Figure 2. Influence of temperature on road surface friction: (a) Ambient temperature (°C), and (b) Pavement temperature (°C).

Figure 2. presents the data collecting related to two other main weather factors, namely ice temperature and possibility of ice on the surface pavement. In respect of the low ice temperature the friction coefficient decreases up to 0.6. (see Figure 3. a). However, the existence of ice possibility (ice layer distribution percentage) on the surface pavement lead to a significant dropping of the friction. For instance, in the winter when ice possibility reaches to 30% the friction decreases to 0.24, which is unacceptable threshold according to different standards [12]. For this reason, in similar cases usually de-icing and de-salting plans [32], [33] are employed in order to guarantee road user's safety (see Figure 4.b, small circle in the right).

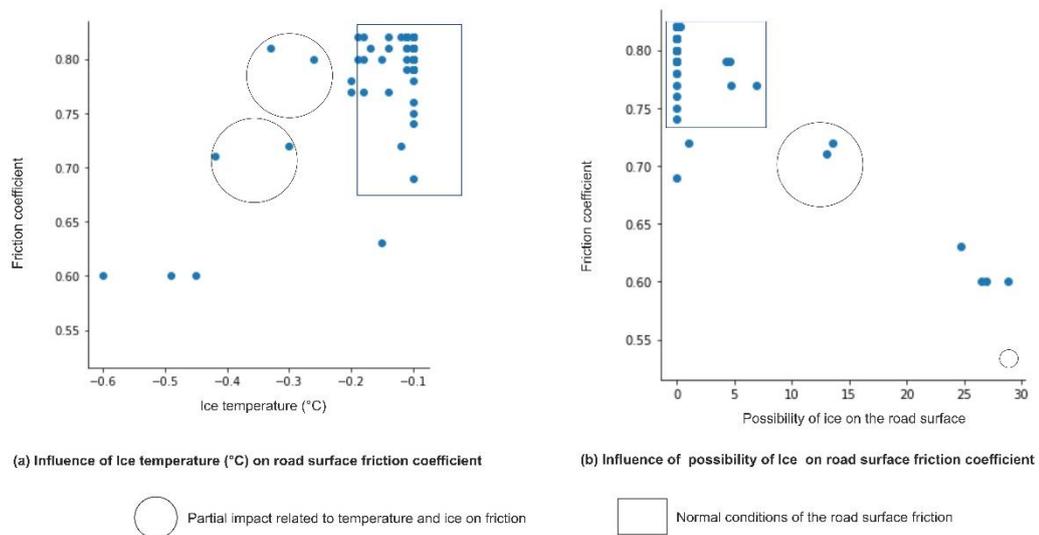


Figure 3. Influence of (a) Ice temperature (°C), and (b) Ice possibility on road surface (%) on road surface friction.

Water film thickness is one of the main weather conditions factors occurring after a rainfall, which can significantly influence the reliable functionality of the road pavement friction. An increase of water film thickness could cause a decrease in the road surface friction [30]. Figure 3. a show the increase in water film thickness would cause decrease in pavement friction coefficient: when water film thickness reaches 1250 (µm) surface pavement friction decrease up to 0.55. Additionally, road conditions (e.g., dry, moist, damp, ice covered, snow and chemically wet) can influence the reliable transportation of goods and people in road pavements. Figure 3. b shows during damp (moist) and wet road condition (coding represents in-between 20-255, which is a mix of water and conditions of ice, which is considered wet condition), this is the most frequent condition when friction decreases. In a case of chemically wet or contaminated road pavement surface (see figure 4. b, horizontal axis 35) friction dramatically reaches unsafe value which is 0.24, this could be also partially related to the existence of possibility of ice (Figure 2. b).

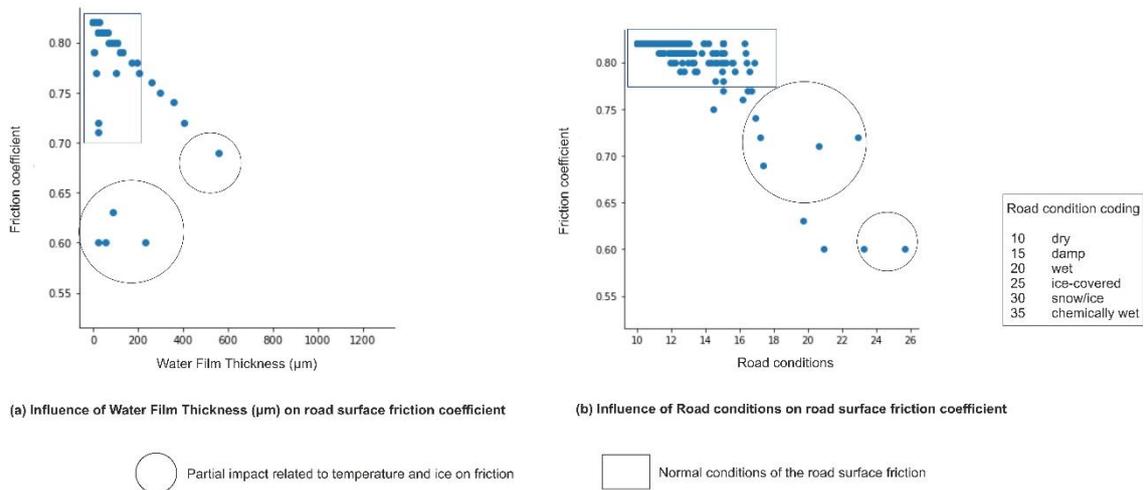


Figure 4. Influence of (a) Water Film Thickness (µm), and (b) Road conditions on road surface friction.

Table 1 shows some critical condition in the different periods of the year including winter and summer season, the relevant and partial influence or more precisely the interaction between two parameters can be observed. For instance, in the point 4 (P4) during winter ice possibility is around 24.76 and water film thickness is 88.49 µm which decreases friction coefficient to 0.63. Here, probably the interaction between ice and water influence the road surface friction. More researches are needed in order to find the interaction between parameters and their influence on the friction.

Table 1. Critical weather conditions for some specific points (not all data) on the Spanish case study.

No	Time	Season	Friction coefficient	Water Film thickness (µm)	Possibility of ice on road surface	Road condition (see table 3)
P1	2019/12/20 00:00 - 2019/12/20 23:59	Winter	0.69	559.45	0.00	17.36
P2	2020/03/31 00:00 - 2020/03/31 23:59	Winter-Spring	0.72	403.39	1.00	22.90

P3	2020/05/31 00:00 - 2020/05/31 23:59	Spring- Summer	0.53	1275.32	0.00	20.00
P4	2021/01/08 00:00 - 2021/01/08 23:59	Winter	0.63	88.49	24.76	19.70

3.2 Pre-assessment thresholds and possible action of road surface friction

According to the current procedure, the friction coefficient is monitored in a non-steady basis to ensure the good state of the road surface for drivers, but it does not consider the effect of climatic conditions. This study introduces the effect of the climatic condition on friction coefficient.

Even though the road surface should remain in a good state according to the squid resistance standards, but it is useful to be aware about the effect of climatic conditions in instantaneous friction coefficient. In order to use this valuable information as input when making decisions on instantaneous traffic management (e.g., control of maximum velocity).

For this reason, defining possible thresholds of road surface friction value with potential actions based on different condition is essential. As a consequence of this study and considering local authorities' thresholds for traffic management system, three main thresholds are defined for this specific case study taking into account the global standards of the most stable friction coefficient.

Table 2 presents thresholds of the friction with possible actions of monitoring of road pavement associated to thresholds of friction coefficient.

No.	Thresholds (Friction coefficient)	Conditions	Possible actions	Monitoring level
1	0.30	Critical	An urgent action is needed (e.g., maintenance)	Intervention level [20]
2	0.60	Acceptable low	Frequent monitoring and traffic management plan (TMP) e.g. control of maximum velocity	Intervention level [20]
3	0.80	Optimal	Normal TMP	Investigatory level [20]

4 CONCLUSIONS AND FUTURE WORKS

Reliable road pavement is dominant infrastructure for both human safe transportation and economy growth, specifically with a vast growth in the traffic management system in Europe and worldwide [30], [34], [35]. In order to provide a comprehensive knowledge on road system network various factors should be taking into account (e.g., weather conditions, pavement texture, human behaviour, lighting and visibility, signals and road marking, safety instructions). In this research paper, the influence of weather conditions on road surface friction is investigated by means intelligent road-based passive sensor. This work concludes that the relation between several weather condition related factors on the road surface friction in real scale case study. The final remarks for this preliminary study are:

- The use of intelligent road-based passive sensor for 18 months weather condition data related recorded in a real scale case study in Spain. The relation between weather condition, road surface friction is presented in this work. Results show that the most reliable friction coefficient thresholds alarms are considered by Spanish authority, and previous knowledge is 0.80 optimal friction coefficient, which is considered standard condition. On the other hand, a frequent monitoring of the road surface is essential when the friction coefficient decrease to less than 0.60, and less than 0.30 could be considered an urgent condition (see Table 2), and in this case an urgent maintenance of the road surface is needed, specifically in case of extreme weather condition such as ice or snow.

- The most extreme weather condition factors (the weather factors which can influence the road surface friction stability) have significant impact on road surface friction are the increase of ice-percentage and water film thickness on the road surface (see Table 3).
- Ambient (air) and pavement temperatures have slightly similar influence on road surface friction. Which can be considered as an in-direct factors or partially influence the road surface friction and accident rates.
- Beside other intervention factors can also affect the friction stability, which are age, texture depth, abrasion and other macro texture properties such a case study of [36]. This study has considered a preliminary finding of the main relation between road surface friction and weather condition related factors.
- This study provides a decision-making support tool for end-users, and owners/operators in charge of the operation of the road network. This model has been integrated to the holistic novel platform of the PANOPTIS project funded by European Union in order to increase resilience of road transport infrastructure.
- This work will be extended for future/and on-going project by using machine learning approaches. In the context of machine learning application for forecasting prediction of friction coefficient and use of real-time monitoring of friction coefficient [37].

Table 3. Summary results of the influence of the critical weather conditions on road surface friction.

No.	Road surface	Weather conditions	Critical values	Surface friction	Friction Reduction Percentage (%)	Figure
1	Temperature	Ambient (°C)	-3	0.59	26.25	3.a
		Pavement (°C)	-2	0.58	27.5	3.b
		Ice (°C)	-0.5	0.58	27.5	4.a
2	Conditions	Possibility of ice on surface	80	0.24	70.00	4.b
		Water film thickness (µm)	1250	0.55	31.25	5.a
		Road conditions	35	0.24	70.00	5.b

AUTHOR CONTRIBUTIONS

Mezgeen Rasol: conceptualization, investigation, methodology, resources, software, validation, visualization, writing original draft, writing - review & editing. Franziska Schmidt: conceptualization, project administration, supervision, revision. Silvia Ientile: revision, and idea exchanges.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreements No. 769129. Authors acknowledge the financial support from Gustave Eiffel University and a special thanks to the ACCIONA company and their on-site monitoring team for providing us dataset. The Project acknowledges the support of the Spanish Ministry of Transport, Mobility and Urban Agenda in the integration of PANOPTIS technologies, part of the Spanish Network of first-generation highways.

PREFERENCES

- [1] C. Liu, Y. Zhan, Q. Deng, Y. Qiu, and A. Zhang, 'An improved differential box counting method to measure fractal dimensions for pavement surface skid resistance evaluation', *Measurement*, vol. 178, no. January, p. 109376, 2021, doi: 10.1016/j.measurement.2021.109376.

- [2] R. B. Kogbara, E. A. Masad, E. Kassem, A. Scarpas, and K. Anupam, 'A state-of-the-art review of parameters influencing measurement and modeling of skid resistance of asphalt pavements', *Constr. Build. Mater.*, vol. 114, pp. 602–617, 2016, doi: 10.1016/j.conbuildmat.2016.04.002.
- [3] B. Choubane, C. R. Holzschuher, and S. Gokhale, 'Precision of locked-wheel testers for measurement of roadway surface friction characteristics', *Transp. Res. Rec.*, no. 1869, pp. 145–151, 2004, doi: 10.3141/1869-17.
- [4] W. Bergman, 'Skid Resistance Properties of Tires and Their Influence on Vehicle Control.', *Transp. Res. Rec.*, no. 621, pp. 8–18, 1976.
- [5] T. Li, 'A state-of-the-art review of measurement techniques on tire–pavement interaction noise', *Meas. J. Int. Meas. Confed.*, vol. 128, no. April, pp. 325–351, 2018, doi: 10.1016/j.measurement.2018.06.056.
- [6] M. T. Do *et al.*, 'Prediction of Tire / Wet Road Friction from Road Surface Microtexture and Tire Rubber Properties To cite this version : Prediction of Tire / Wet Road Friction from Road Surface Microtexture and Tire Rubber Properties', 2013.
- [7] S. Kim, J. Lee, and T. Yoon, 'Road surface conditions forecasting in rainy weather using artificial neural networks', *Saf. Sci.*, vol. 140, no. April, p. 105302, 2021, doi: 10.1016/j.ssci.2021.105302.
- [8] Z. Li *et al.*, 'Investigation of driver injury severities in rural single-vehicle crashes under rain conditions using mixed logit and latent class models', *Accid. Anal. Prev.*, vol. 124, pp. 219–229, 2019, doi: <https://doi.org/10.1016/j.aap.2018.12.020>.
- [9] A. J. McMillan *et al.*, 'A review of composite product data interoperability and product life-cycle management challenges in the composites industry', *Adv. Manuf. Polym. Compos. Sci.*, vol. 3, no. 4, pp. 130–147, 2017, doi: 10.1080/20550340.2017.1389047.
- [10] S. K. Srirangam, K. Anupam, C. Kasbergen, A. Scarpas, and V. Cerezo, 'Study of Influence of Operating Parameters on Braking Friction and Rolling Resistance', *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2525, no. 1, pp. 79–90, 2015, doi: 10.3141/2525-09.
- [11] Y. Beautru, M. Kane, V. Cerezo, and M.-T. Do, 'Effect of thin water film on tire/road friction', *Young Res. Semin. (YRS 2011)*, no. June, 2011.
- [12] L. J. Chu and T. F. Fwa, 'Pavement skid resistance consideration in rain-related wet-weather speed limits determination', *Road Mater. Pavement Des.*, vol. 19, no. 2, pp. 334–352, 2018, doi: 10.1080/14680629.2016.1261723.
- [13] C. Plati, M. Pomoni, and K. Georgouli, 'Quantification of skid resistance seasonal variation in asphalt pavements', *J. Traffic Transp. Eng. (English Ed.)*, vol. 7, no. 2, pp. 237–248, 2020, doi: 10.1016/j.jtte.2018.07.003.
- [14] W. R. Tyfour, 'Tire Skid Resistance on Contaminated Wet Pavements', vol. 3, no. 2, pp. 119–124, 2009.
- [15] A. Ueckermann, D. Wang, M. Oeser, and B. Steinauer, 'Calculation of skid resistance from texture measurements', *J. Traffic Transp. Eng. (English Ed.)*, vol. 2, no. 1, pp. 3–16, 2015, doi: 10.1016/j.jtte.2015.01.001.
- [16] W. van Bijsterveld and M. A. del Val, 'Towards quantification of seasonal variations in skid resistance measurements', *Road Mater. Pavement Des.*, vol. 17, no. 2, pp. 477–486, 2016, doi: 10.1080/14680629.2015.1090909.
- [17] Y. Zan, Z. Li, G. Su, and X. Zhang, 'An innovative vehicle-mounted GPR technique for fast and efficient monitoring of tunnel lining structural conditions', *Case Stud. Nondestruct. Test. Eval.*, 2016, doi: 10.1016/j.csndt.2016.10.001.
- [18] A. W. Black, G. Villarini, and T. L. Mote, 'Effects of rainfall on vehicle crashes in six U.S. states', *Weather. Clim. Soc.*, vol. 9, no. 1, pp. 53–70, 2017, doi: 10.1175/WCAS-D-16-0035.1.
- [19] D. M. Tobin, M. R. Kumjian, and A. W. Black, 'Characteristics of recent vehicle-related fatalities during active precipitation in the United States', *Weather. Clim. Soc.*, vol. 11, no. 4, pp. 935–952, 2019, doi: 10.1175/wcas-d-18-0110.1.
- [20] M. Rasol *et al.*, 'Progress and Monitoring Opportunities of Skid Resistance in Road Transport : A Critical Review and Road Sensors', 2021.
- [21] S. N. Runkle and D. C. Mahone, *Variations in Skid Resistance Over Time. Part I. Final Report*. 1980.
- [22] M. A. Khasawneh and R. Y. Liang, 'Temperature effect on frictional properties of HMA at different polishing stages', *Jordan J. Civ. Eng.*, vol. 6, no. 1, pp. 39–53, 2012.
- [23] and L. A. W. A. R. L. Rizenbergs, J. L. Burchett, 'ACCIDENTS ON RURAL, TWO-LANE ROADS AND THEIR RELATION TO PAVEMENT FRICTION by R. L. Rizenbergs, J. L. Burchett, and L. A. Warren', Kentucky, 1976. doi: 10.13023/KTC.RR.1976.458.
- [24] Minh-Tan Do, Veronique Cerezo, Yannick Beautru, and Malal Kane, 'Influence of Thin Water

- Film on Skid Resistance', *J. Traffic Transp. Eng.*, vol. 2, no. 6, 2014, doi: 10.17265/2328-2142/2014.06.004.
- [25] Y. Liu, T. F. Fwa, and Y. S. Choo, 'Finite-element modeling of skid resistance test', *J. Transp. Eng.*, vol. 129, no. 3, pp. 316–321, 2003, doi: 10.1061/(ASCE)0733-947X(2003)129:3(316).
- [26] T. F. Fwa and L. Chu, 'The concept of pavement skid resistance state', *Road Mater. Pavement Des.*, vol. 22, no. 1, pp. 101–120, 2021, doi: 10.1080/14680629.2019.1618366.
- [27] and G. N. S. Mitchell, J.C., M.I. Phillips, 'Report No. FHWA/MD-86/02: Seasonal Variation of Friction Numbers', *Maryl. Dep. Transp. (MDOT), Balt.*, 1985.
- [28] Panoptis, 'PANOPTIS Horizon 2020 project (Grant No. 769129). <http://www.panoptis.eu/>', 2021.
- [29] E. Pais, 'http://elpais.com/diario/2000/06/13/espana/960847215_850215.html', *el pais*, 2000. .
- [30] M. Rasol *et al.*, 'Progress and Monitoring Opportunities of Skid Resistance in Road Transport : A Critical Review and Road Sensors', *Remote Sens.*, vol. 13, no. 18, pp. 1–27, 2021, [Online]. Available: <https://www.mdpi.com/2072-4292/13/18/3729>.
- [31] DMRB, 'CS 228 Skidding resistance', 2020.
- [32] M. Yu, Z. You, G. Wu, L. Kong, C. Liu, and J. Gao, 'Measurement and modeling of skid resistance of asphalt pavement: A review', *Constr. Build. Mater.*, vol. 260, p. 119878, 2020, doi: 10.1016/j.conbuildmat.2020.119878.
- [33] W. R. Trenouth, B. Gharabaghi, and N. Perera, 'Road salt application planning tool for winter de-icing operations', *J. Hydrol.*, vol. 524, pp. 401–410, 2015, doi: 10.1016/j.jhydrol.2015.03.004.
- [34] Mezgeen Rasol, 'Development of New GPR Methodologies for Soil and Cement Concrete Pavement Assessment Mezgeen Abdulrahman Rasol Rasol', Polytechnic University of Catalonia (UPC), 2021.
- [35] V. Perez-Gracia, S. Santos-Assunção, O. Caselles, J. Clapes, and V. Sossa, 'Combining ground penetrating radar and seismic surveys in the assessment of cultural heritage buildings: The study of roofs, columns, and ground of the gothic church Santa Maria del Mar, in Barcelona (Spain)', *Struct. Control Heal. Monit.*, vol. 26, no. 4, p. e2327, 2019, doi: 10.1002/stc.2327.
- [36] K. Athiappan, A. Kandasamy, M. J. Sheik, P. Parthiban, and S. Balasubramanian, 'Materials Today : Proceedings Prediction modeling of skid resistance and texture depth on flexible pavement for urban roads', *Mater. Today Proc.*, no. xxxx, 2022, doi: 10.1016/j.matpr.2021.10.304.
- [37] M. Rasol, F. Schmidt, and S. Ientile, 'Road surface friction measurement based on intelligent road sensor and machine learning approaches' EGU General Assesmbly 2022, Vienna, Austria, vol. 769129, no. 769129, p. 769129, 2022.