Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 3.2
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.3.2

From Humidity to Squeal: Laboratory Insights into Humidity-Driven Changes in Wheel-Rail Friction

M. Omasta, M. Škubna, M. Valena, R. Galas, I. Křupka and M. Hartl

Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic

Abstract

Environmental moisture strongly affects wheel–rail friction and friction states relevant to curve noise in urban rail systems. Although increasing relative humidity is generally expected to reduce adhesion, field observations indicate that humid periods may be associated with friction conditions that lead to increased curve noise. This paper investigates the underlying contradiction through laboratory experiments on a rail segment using a portable rail tribometer, a controlled climatic chamber, and a rolling–sliding contact simulator. The results confirm the classical short-term effect of humidity, with decreased adhesion, while prolonged exposure to high humidity or direct water exposure leads to a delayed increase in dry adhesion due to oxide and oxyhydroxide layer formation. Subsequent dry wheel passages further increase adhesion by mechanically conditioning the running band. The study demonstrates that the final friction state is governed by the coupling between moisture-driven tribochemical surface preparation and subsequent traffic-induced mechanical activation.

Keywords: wheel-rail interface, friction, humidity, oxidation, water contamination, squealing.

1 Introduction

Wheel–rail squeal remains one of the most persistent operational challenges in urban rail transport, particularly in tight curves where unstable frictional oscillations are easily excited. The phenomenon is strongly governed by the local wheel–rail friction conditions, surface roughness evolution, and the formation of third-body layers within the open tribological system [1][2][3][4][5]. Humidity and moisture are generally considered key environmental parameters that control friction and adhesion in steel rolling–sliding contacts [6][7][8].

A widely accepted conclusion in wheel-rail tribology is that increasing ambient relative humidity (RH) reduces friction. This effect is commonly attributed to thin adsorbed water films, capillary interactions, and moisture-assisted modification of oxide debris layers. Several laboratory studies using pin-on-disc, twin-disc, and mini-traction machine configurations have reported a nearly monotonic decrease in adhesion with increasing RH, particularly under controlled clean-surface conditions [6][7][9]. Similar trends have also been reported for high-temperature railhead conditions, where humidity suppresses adhesion and alters surface-damage evolution [10].

However, the real railway environment represents a significantly more complex tribological system than simplified laboratory contacts. In open wheel–rail operation, friction is not determined solely by the instantaneous presence of moisture, but also by time-dependent tribochemical transformations of the rail surface. Previous studies have shown that naturally formed iron oxides, oxyhydroxides, and moisture-dependent reaction products may substantially modify friction behavior, particularly under wet-rail and dew conditions [11][12][13][14]. The transformation pathways between hematite, magnetite, goethite, and lepidocrocite are especially sensitive to cyclic wetting, drying, and repeated wheel passages [8][15].

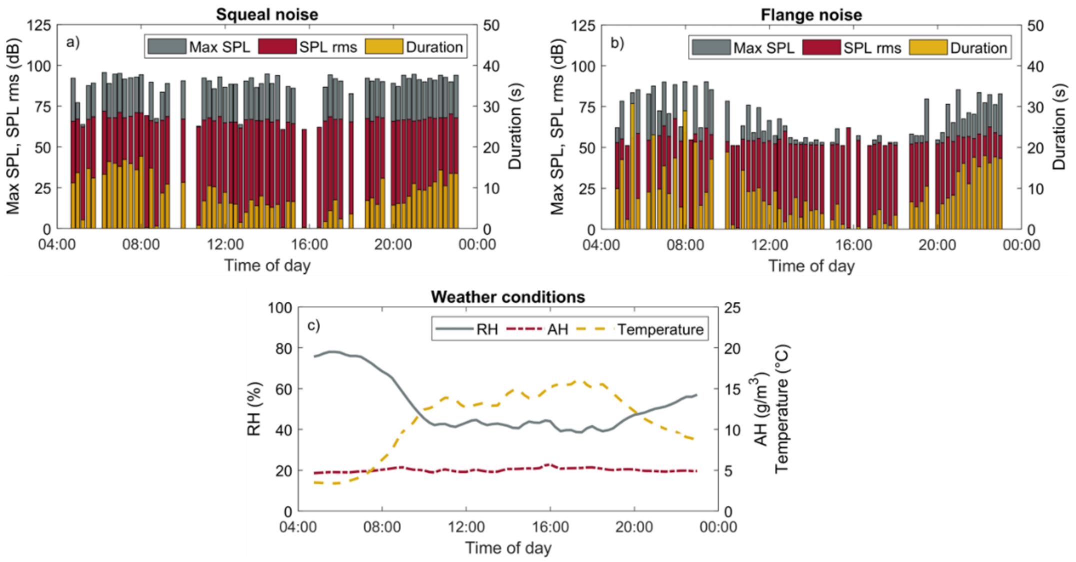

Figure 1: Daily variation of squeal noise (a), flange noise (b), and weather conditions (c). Adapted from [16], licensed under CC BY 4.0. Changes include cropping.

This complexity becomes particularly important when interpreting field observations related to curve squeal. In our previous in-service monitoring study of tram squeal events, periods of elevated ambient RH were associated with a higher frequency of squeal occurrences, despite the classical expectation of reduced friction under humid conditions, as illustrated in Figure 1 [16]. The literature contains studies with both similar [2] and contradictory [17] conclusions. This operational evidence suggests that the commonly accepted instantaneous RH–friction relationship may be insufficient for explaining squeal in real rail systems.

A plausible explanation is that humidity acts not only as a short-term friction modifier, but also as a driver of oxide and hydrate layer evolution on the railhead. These naturally forming layers may alter the traction curve slope, promote intermittent stick–slip behavior, and shift the system toward frictional instability. Under repeated rolling–sliding passages, humidity-assisted tribochemical layers may therefore lead to friction states that differ fundamentally from those predicted by conventional fixed-slip laboratory tests. Despite extensive prior work on wet-rail adhesion and oxide-contaminated contacts, the link between humidity-driven surface-chemistry evolution and squeal-promoting friction conditions remains poorly understood.

To address this gap, the present study combines field-inspired motivation with controlled laboratory testing on real rail specimens using a portable rail tribometer capable of measuring complete traction curves. The work specifically focuses on how relative humidity and controlled water exposure influence the formation, transformation, and mechanical persistence of oxide-based third-body layers that may govern squeal-relevant friction behavior.

2 Methods

This experimental lab-scale work was performed on a 1500 mm long R65 rail segment, enabling the use of a realistic railhead geometry. To simulate the cumulative effect of repeated wheel passages, a wheel–rail contact simulator (Figure 2 (b)) was employed. The simulator consists of a 150 mm-diameter steel wheel rolling over the rail segment at a controlled constant creepage of 1.67% and a contact pressure up to 0.8 GPa, corresponding to light-rail traffic operational wheel–rail pressures.

After rail surface conditioning using the contact simulator, a portable rail tribometer (Figure 2(a)) [18] was used to measure a traction curve. The tribometer uses a 100 mm measuring wheel and allows contact pressures up to 1 GPa, with a test speed of 0.4 m/s. During the test run, the wheel is braked with an increasing braking torque, while the reaction torque is measured and the slip between the rail and the disc is evaluated. The result is a full traction curve over the creep range of 0–100%. From this curve, an "average" value is determined within a creep range of 5–30%, which reliably corresponds to the saturation of the adhesion coefficient. This configuration enables the evaluation of adhesion under conditions directly transferable to field measurements.

A custom climatic chamber was developed around the rail segment (Figure 2 (c)), allowing the enclosure of both the rail tribometer or contact simulator to enable controlled relative humidity (RH) exposure. The RH was varied between 30% and 95%, while the ambient temperature was maintained at 23–24 °C.

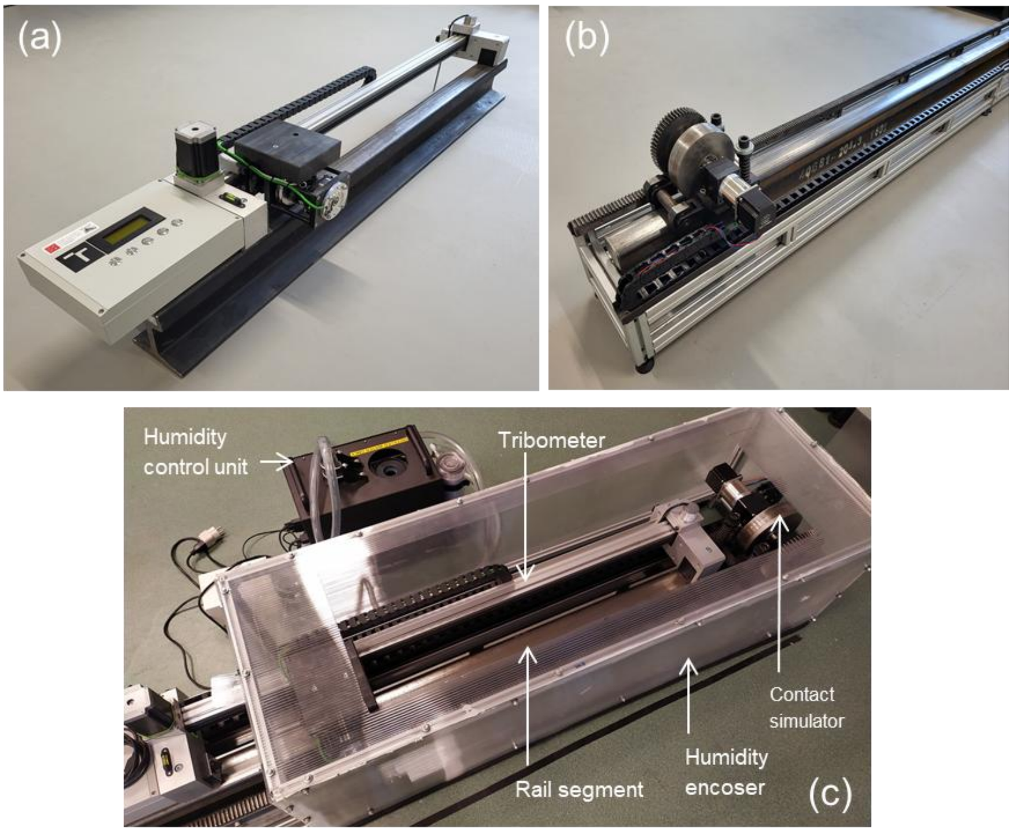

Figure 2: Experimental devices used. (a) BUT Rail tribometer, (b) Wheel-rail contact simulator and (c) experimental setup with humidity control unit and chamber.

This study includes various tests that differ in the conditions under which the friction layer was prepared and those under which adhesion was measured on that layer. Both processes were performed under dry conditions (at room temperature of 24 °C and RH of 30%), under controlled RH, or with water applied to the rail surface. The specific preparation method is described for each result. Each test was preceded by a brief run-in period using a contact simulator (up to 10 passes) to achieve a comparable baseline for the coefficient of adhesion.

3 Results

3.1 The effect of instantaneous air humidity

During the test, the rail tribometer was placed inside the climatic chamber and traction curves were measured after RH stabilization at 30, 40, 50, 65, 75, 85 and 95%. Measurements with a tribometer in the climate chamber show a gradual decrease in adhesion with increasing relative humidity (Figure 3). At 30% RH, the average adhesion coefficient was approximately 0.30, while at 95% RH it decreased to 0.15. The decrease was gradual up to approximately 65% RH, above which a steeper reduction was observed.

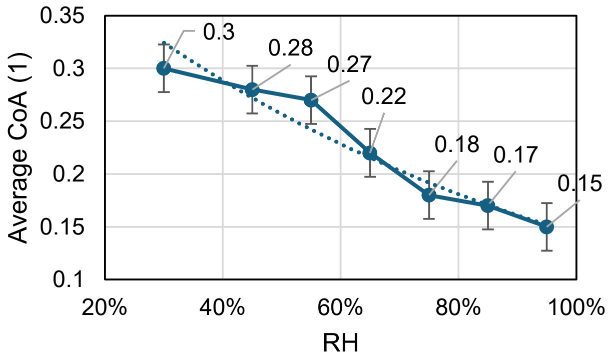

Figure 3: Average adhesion coefficient as a function of ambient relative humidity measured immediately after RH stabilization.

This result is consistent with the conventional interpretation that adsorbed moisture layers and water-assisted third-body films reduce direct steel–steel contact and therefore lower friction. From a railway engineering perspective, this confirms that instantaneous humid conditions alone cannot explain the increased squeal frequency observed in field measurements.

3.2 The effect of air humidity after prolonged exposure

In this experiment, the rail surface was exposed to RH = 95% for dwell periods of 1 h, 3 h and 8 h, after which adhesion was measured under laboratory (room) RH conditions (Figure 4). A substantially different trend was observed when the rail surface was exposed to high RH for prolonged periods.

After exposure at 95% RH, subsequent adhesion measurements under ambient laboratory conditions showed a progressive increase rather than a decrease. The increase was more pronounced with longer exposure to humid air. This indicates that humidity induces time-dependent surface transformations, most likely related to the formation of thin oxide and oxyhydroxide layers. This result represents the key paradox of the study, i.e., the instantaneous RH reduces adhesion, whereas prolonged humid exposure may increase adhesion after drying or partial surface conditioning. This delayed effect provides a plausible explanation for the higher squeal occurrence observed during humid nights and early morning tram operation.

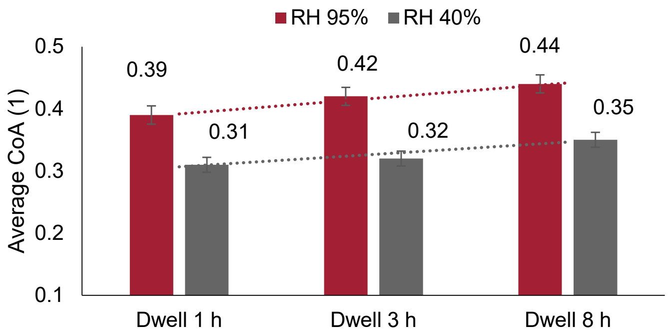

Figure 4: Average adhesion coefficient measured after prolonged exposure at RH 40% and 95%, followed by testing under ambient laboratory conditions.

3.3 The effect of water after prolonged exposure

To extend the humidity-memory concept toward an extreme environmental case, additional experiments were performed using direct water exposure as a limiting form of prolonged high-humidity action. To ensure long-term wetting of the rail surface, a fabric strip soaked with distilled water was laid on the rail.

Measurements of the adhesion coefficient were taken at specified intervals, either while the rail surface was still wet or after the water had dried. For dry measurements, adhesion (Figure 5) increased from approximately 0.36 after 1 h to 0.52 after 16 h of water exposure. In contrast, under wet conditions, adhesion remained significantly lower, with the most pronounced reduction observed after 1 h, where the adhesion coefficient reached approximately 0.27.

The photographs in Figure 5 show the rail surface after 1 and 16 hours. Gradual oxidation is evident, leading to the formation of oxyhydroxides (likely α-FeOOH and γ-FeOOH). These results show that the formation of oxide hydrates due to the presence of water can significantly increase friction, whereas the immediate presence of water tends to reduce this value—a phenomenon well described in the literature as the wet-rail phenomenon [6][14]. This behavior strongly supports the central hypothesis of the paper: the rail surface state is governed not only by the presence of moisture, but also by the history-dependent evolution of oxide and oxyhydroxide layers. From an operational perspective, this experiment represents a realistic analog of overnight rain, dew accumulation, or standing moisture in low-traffic curves, followed by the first vehicle passages after surface drying.

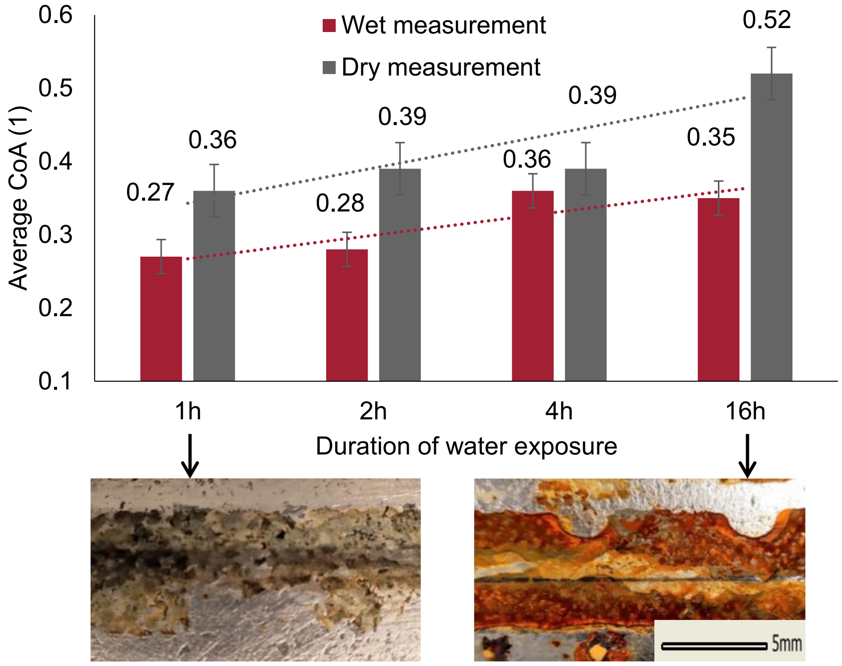

Figure 5: Average adhesion coefficient after prolonged water exposure, followed by testing under ambient wet or dry conditions.

3.4 The effect of repeated wheel passes

In actual operation, the formation, transformation, and durability of third-body layers are strongly influenced by the passage of rail vehicles. Repeated dry rolling–sliding passages were used as a reference mechanical conditioning scenario, enabling the separation of purely mechanical running-band evolution from humidity-driven tribochemical effects. As shown in Figure 6, adhesion increased from approximately 0.30 in the initial state to 0.41 after 100 passes, followed by a slight decrease to 0.37 after 150 passes. The accompanying surface images reveal progressive smoothing of the running band, accompanied by the formation of dark, oxide-rich third-body material, predominantly magnetite (Fe_3O_4).

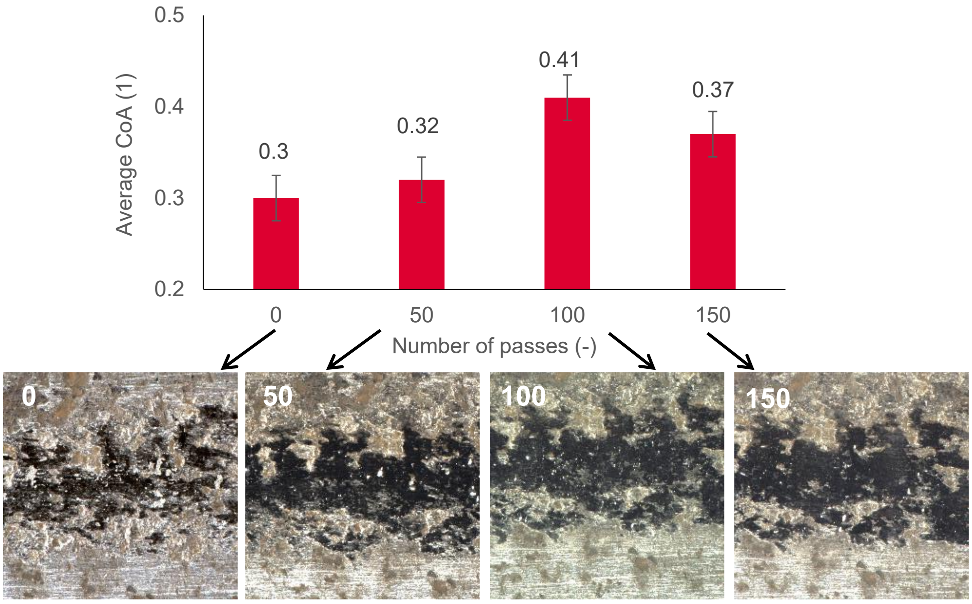

Figure 6: Evolution of average adhesion coefficient during repeated dry rolling–sliding passages.

These results indicate that environmental moisture primarily prepares the rail surface through delayed tribochemical transformations, whereas the final friction state is strongly influenced by subsequent traffic-induced mechanical conditioning. The coupling between these two processes appears to be critical for understanding the transition toward squeal-prone operating conditions.

4 Conclusions and Contributions

The present study investigated the effect of environmental humidity, direct water exposure, and repeated wheel passages on wheel–rail adhesion using a real rail segment, full traction-curve measurements, and controlled laboratory humidity conditioning.

The principal findings can be summarized as follows:

- Instantaneous humidity decreases adhesion, confirming the classical tribological behavior of humid steel rolling–sliding contacts.
- Prolonged exposure to high RH leads to a delayed increase in adhesion after drying, demonstrating a clear humidity-memory effect associated with tribochemical surface transformations.
- Direct water exposure acts as an extreme form of the same mechanism, accelerating oxide-hydrate formation and producing an even stronger delayed increase in dry adhesion.
- Repeated dry wheel passages mechanically activate and stabilize the prepared surface, leading to additional adhesion increase through running-band smoothing and redistribution of oxide-rich third-body layers.

The main contribution of the work is the demonstration that the wheel–rail interface is governed not only by the instantaneous environmental state, but also by the history of moisture exposure and subsequent traffic conditioning. This provides a practical explanation for the increased squeal occurrence observed after humid nights, dew formation, or rainfall followed by the first dry vehicle passages, and establishes an experimentally supported framework for future humidity-aware squeal-risk prediction and friction-management strategies.

Acknowledgements

This research was carried out within the Lead Agency project “Friction phenomena in rolling contacts caused by suspensions”, jointly funded by the Czech Science Foundation (GA ČR, project GF24-14624L) and the Austrian Science Fund (FWF, project PIN8512323). Financial support for this publication was provided by the "Mechanical Engineering of Biological and Bio-inspired Systems" project funded as a project No. CZ.02.01.01/00/22_008/0004634 by Programme Johannes Amos Comenius, call Excellent Research.

References

[1] F.G. de Beer, M.H.A. Janssens, P.P. Kooijman, "Squeal noise of rail-bound vehicles influenced by lateral contact position", *Journal of Sound and Vibration*, 267(3), 497-507, 2003.

[2] X. Liu, P.A. Meehan, "Investigation of the effect of relative humidity on lateral force in rolling contact and curve squeal", *Wear*, 310(1-2), 12-19, 2014.

[3] U. Olofsson, Y. Lyu, "Open system tribology in the wheel-rail contact: A literature review", *Applied Mechanics Reviews*, 69(6), 060803, 2017.

[4] Y. Lyu, E. Bergseth, U. Olofsson, "Open system tribology and influence of weather condition", *Scientific Reports*, 6, 32455, 2016.

[5] Y. Zhu, Y. Lyu, U. Olofsson, "Mapping the friction between railway wheels and rails focusing on environmental conditions", *Wear*, 324-325, 122-128, 2015.

[6] R. Galas, R. Lewis, U. Olofsson, Y. Lyu, "The low adhesion problem: The effect of environmental conditions on adhesion in rolling-sliding contact", *Tribology International*, 151, 106521, 2020.

[7] M.O. Folorunso, R. Lewis, J.L. Lanigan, "Effects of temperature and humidity on railhead friction levels", *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit*, 237(8), 1009-1024, 2023.

[8] Y. Zhu, "The influence of iron oxides on wheel-rail contact: A literature review", *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit*, 232(3), 734-743, 2018.

[9] B.T. White, R. Lewis, "Effect of the presence of moisture at the wheel-rail interface during dew and damp conditions", *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit*, 232(4), 979-989, 2018.

[10] K.J. Rong, Y.L. Xiao, M.X. Shen, H.P. Zhao, W.J. Wang, G.Y. Xiong, "Influence of ambient humidity on the adhesion and damage behavior of wheel-rail interface under hot weather condition", *Wear*, 486-487, 204091, 2021.

[11] Y. Zhu, U. Olofsson, H. Chen, "Friction between wheel and rail: A pin-on-disc study of environmental conditions and iron oxides", *Tribology Letters*, 52(2), 327-339, 2013.

[12] Y. Zhu, U. Olofsson, K. Persson, "Investigation of factors influencing wheel-rail adhesion using a mini-traction machine", *Wear*, 292-293, 218-231, 2012.

[13] C. Hardwick, R. Lewis, U. Olofsson, "Low adhesion due to oxide formation in the presence of salt", *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit*, 228(8), 887-897, 2014.

[14] R. Kempka, R. Falconer, D. Gutsulyak, R. Lewis, "Effects of oxide and water on friction of rail steel - new test method and friction mapping", *Tribology - Materials, Surfaces and Interfaces*, 15(2), 80-91, 2021.

[15] J. Suzumura, Y. Sone, A. Ishizaki, D. Yamashita, Y. Nakajima, M. Ishida, "In situ X-ray analytical study on the alteration process of iron oxide layers at the railhead surface while under railway traffic", *Wear*, 271(1-2), 47-53, 2011.

[16] M. Valena, M. Omasta, M. Klapka et al., "Case study: correlations between curve squeal, weather conditions, and traction in a tram loop", *Tribology in Industry*, 46(4), 695-708, 2024.

[17] L. Toratti, M. Asplund, F. Thiery et al., "Statistical analysis of railway curve squeal occurrence on the low and high rails in relation to environmental conditions", *Railway Engineering Science*, 2026, in press.

[18] M. Valena, M. Omasta, D. Kvarda, R. Galas, I. Krupka, M. Hartl, "An approach for the creep-curve assessment using a new rail tribometer", *Tribology International*, 191, 109153, 2024.