Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 3.14
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.3.14

Assessing the Effect of Environmental Conditions on the Performance of Oil-Based Top-of-Rail Friction Modifiers

M. Freisinger[1], N. Ritter[2] and G. Vuilleme[2]

[1]Materials, AC2T research GmbH, Wiener Neustadt, Austria
[2]RAILplus AG, Aarau, Switzerland

Abstract

The performance of top-of-rail friction modifiers (TOR-FMs) is critical for balancing traction, braking, and wear in railway systems, yet is strongly influenced by environmental conditions. This study evaluates the effect of temperature and humidity on oil-based TOR-FMs in Swiss metre-gauge railways using a high-load twin-disc tribometer equipped with a custom climate chamber. Wheel and rail specimens were subjected to controlled winter, summer, and wet/snow-like conditions, while friction coefficients (CoF) and film stability were monitored. Results show, that low temperatures (≤0°C) and high humidity (90 %) produce low and stable CoF (~0.10 – 0.15) over extended cycles, whereas increasing temperatures (15 – 35°C) and lower humidity (25 – 60 %) substantially reduce TOR-FM durability, accelerating the rise of CoF. The study further highlights the importance of precise sensor placement and climate chamber design in capturing realistic wheel-rail interactions. Findings validate current Swiss operational strategies, such as suspending TOR-FM application above 80 % humidity, and suggest optimized application strategies under high-temperature, low-humidity conditions to enhance traction, reduce wear, and mitigate noise effectively. This work underscores the critical role of environmental factors in TOR-FM effectiveness and provides a framework for systematic laboratory evaluation under representative weather conditions.

Keywords: wheel-rail interaction, friction modifier, flange lubricant, twin disc testing.

1 Introduction

Railway systems depend on a careful balance of adhesion and friction at the wheel–rail interface to ensure safe and efficient operation. Excessive friction accelerates wear, while insufficient friction reduces traction and braking. Top-of-rail friction modifiers (TOR-FMs) are therefore used to reduce wear, noise, and energy loss while maintaining adequate adhesion [1], [2], [3]. TOR-FMs are broadly categorized into water-based and oil-based formulations. Water-based products use water as a carrier that evaporates after application and are typically used for moderate axle loads, whereas oil-based or hybrid formulations provide more persistent lubrication and are common in heavy-haul systems. In Swiss metre-gauge railways, oil-based TOR-FMs applied by onboard systems effectively reduce wear and noise in curves while preserving traction and braking performance. However, the open wheel–rail contact is strongly influenced by environmental conditions, with temperature, humidity, and water affecting friction levels [4], [5], [6], [7], [8], [9].
Mountainous regions such as alpine railways experience strong seasonal and diurnal variations, including frost, snow, rain, and humidity extremes, which can alter TOR-FM effectiveness. Previous studies have mainly focused on water-based products. Li et al. [10] showed that poor low-temperature performance can increase wear and rolling contact fatigue, while Lewis et al. [11] found friction increases as relative humidity decreases, particularly for water-based products interacting with oxides. Research on oil-based TOR-FMs is limited: Skurka et al. [12] reported that large amounts of water can significantly lower friction for extended periods with oil-based products, and Galas et al. [13], [14] demonstrated that oil-based TOR-FMs can control adhesion but are sensitive to application quantity, affecting braking distance.
Twin-disc testing is the state-of-the-art laboratory method for simulating wheel–rail contact under controlled, repeatable conditions [15], [16], [17], [18], [19], [20], [21]. However, a research gap remains regarding environmental effects on oil-based TOR-FM performance. This study addresses that gap by evaluating oil-based TOR-FMs under representative Swiss metre-gauge weather conditions using a climate-controlled twin-disc test rig, highlighting the influence of temperature and humidity on TOR-FM effectiveness.

2 Methods

The environmental sensitivity of oil-based TOR-FM was evaluated using a custom-built high-load twin-disc tribometer (Figure 1) at AC²T research GmbH, capable of reproducing realistic wheel-rail contact conditions across a wide range of test parameters. The tribometer accommodates two specimens (rail and wheel disc) mounted on independently driven shafts, each rigidly coupled to its respective drive shaft via precision holders, allowing circumferential speeds to be adjusted according to specimen diameter. Power train 1 is fixed to the frame, while power train 2 is mounted on a vertically movable table with guide columns providing lateral support and vertical guidance. Vertical loads are applied via a pneumatic double-acting cylinder mounted on the lower frame. Frictional force at the contact is measured using torque sensors mounted via high-precision metal bellows couplings, while incremental encoders continuously record rotational speeds. The tribometer supports disc widths up to 30 mm, diameters from 50 – 200 mm, speeds of ±6000 rpm, and normal forces up to 20 kN. All specimens are fabricated from original wheel and rail steels. This study employed rail discs (R260 rail steel) of 55 mm diameter and 30 mm width, and wheel discs (ER7 wheel steel) of 130 mm diameter with a contact width of 4 mm. Samples were turned, ground under standardized procedures. To ensure uniform material properties in terms of microstructural characteristics and hardness levels, the disc samples underwent heat treatment procedure before the finishing of the samples.

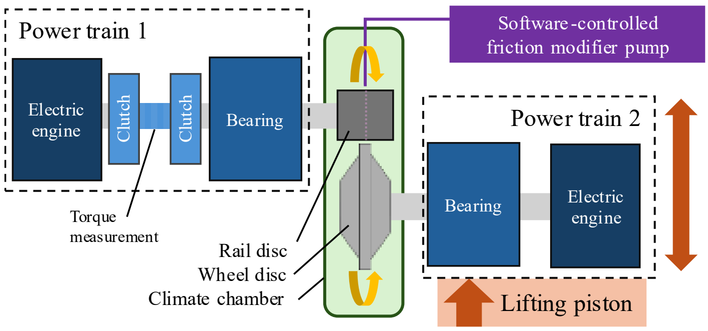

Figure 1: Schematic overview of the high-load twin disc test rig at AC2T research GmbH to assess top-of-rail friction modifier performance under various weather conditions.

Main goal of this study was to assess TOR-FM performance under various weather conditions, as instance in hot summer days when sun radiation can heat up the rail to temperatures above 60°C. To investigate such environmental effects on TOR-FM performance, the discs were enclosed in a custom climate chamber (Figure 2). Temperature and humidity sensors positioned adjacent to the wheel-rail contact allow precise control of environmental conditions directly at the interface. Summer conditions were simulated by heating the rail specimen and its drive shaft up using a hot-air blower, maintaining stable surface and ambient temperatures throughout testing. Winter conditions were achieved using an insulated housing with a cooling system, allowing ambient temperatures down to –10°C. Relative humidity was controlled via humidified air, continuously monitored by calibrated sensors. This setup enabled systematic evaluation of temperature and humidity effects on TOR-FM film stability, friction, and wear.

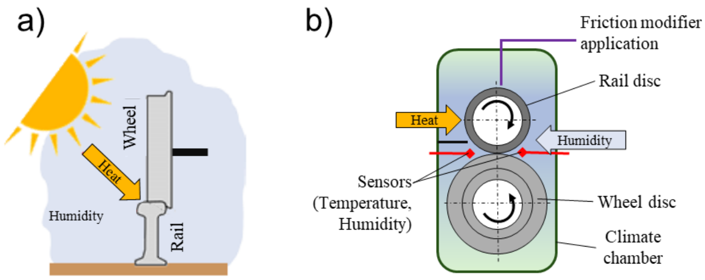

Figure 2: (a) The open system characteristics of the wheel-rail contact, (b) shows the sophisticated climate chamber integrated to the twin disc test rig for this study.

The selected temperatures and humidity levels tested within this study are based on common weather conditions in Swiss metre gauge railway regions [22]. An overview of the tested weather scenarios is given in *Figure 3*. Tests *T1* to *T5* represent common winter to summer situations, whereby the humidity was set to 60 % for these tests to separate the effect of temperature change on the TOR-FM performance, and to consider current systems settings for onboard systems in Swiss metre gauge railways where TOR-FM application is switched off at humidity levels above 80 %. For hot summer condition, test *T6* comes up with heated rail disc (surface temperature 50°C), high air temperature (30°C), and low humidity (25 %). Tests *T7* and *T8* represent light rain, whereby the contact area was initially dry introducing high humidity (90 %) upon test start. The test *T9* is supposed to represent snow condition, interpreted by a wet contact situation (water film) at an ambient temperature of 0°C. No real snow was introduced to the test chamber, since snowflakes are supposed to melt in the actual wheel-rail contact due to frictional heat.

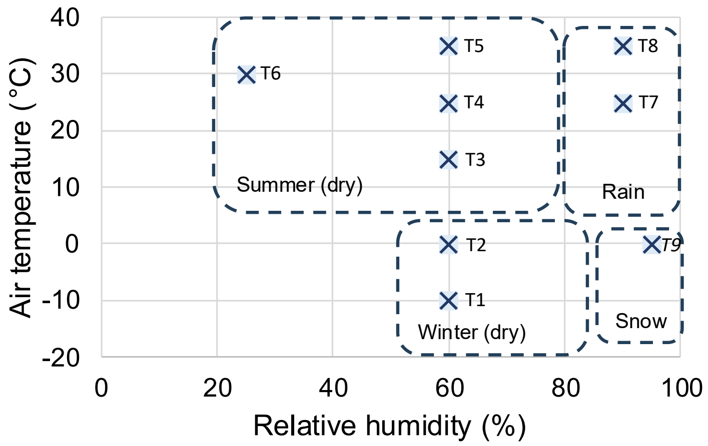

Figure 3: Overview of the environmental settings in the climate chamber of the high-load twin disc tests to simulate various weather conditions.

For each test scenario three twin disc test were performed, whereby a test consisted of a running procedure, the TOR-FM application and the actual friction tests. For the dry running-in procedure adapted from White et al. [23] the rail disc was rotated at 100 rpm without load. In the first stage, wheel and rail specimens were cycled for 100 rotations at negligible sliding-to-rolling ratio (SRR) under a normal force of 1900 N. In the second stage, SRR was set to 2 % while maintaining the same contact pressure, and the procedure continued until the coefficient of friction (CoF) stabilized at approximately 0.40. Following running-in, the specimens were cleaned, and a precise amount of TOR-FM was applied to the rail specimen's circumference using a software-controlled precision application system at a defined dosage of 5.0 mg. Tests were conducted under a defined SRR (1.0 %) and constant contact pressure (1.2 GPa), continuing until the CoF reached 0.40.

3 Results

The results of the high-load twin disc tests are shown by CoF graphs in Figure 4 to Figure 5. All tests start at an initial CoF of ~0.1 followed by a steep increase within the first ~300 cycles, resulting in a stabilization of the CoF. Simulated winter conditions with 60 % humidity and -10°C (*T1*) reveal a low and stable CoF (~0.13) for the entire test duration (Figure 4a). With same humidity but increased temperature (0°C), tests *T2* shows comparable low CoF but a minimal increase over time. At summer conditions, the conducted tests did not run the maximum test duration of 4,000 cycles but reached a CoF of 0.4 earlier (Figure 5). For the tests conducted at 60 % humidity (*T3* – *T5*) the increase of temperature clearly induced a decrease in number of cycles: At 15°C the stop criterion (CoF = 0.4) is reached after ~3,300 cycles (*T3*, Figure 5a), while at 25°C the number of cycles decreased to ~3,100 (*T4*, Figure 5b). The highest ambient temperature (35°C) resulted in a test duration of ~2,900 cycles (*T5*, Figure 5c). Since certain problems from the field in hot and dry summer periods have been reported, twin disc tests with high ambient temperature (30°C) and low humidity (25%) have been performed, with test results underlining the massive effect on TOR-FM performance (*T6*, Figure 5d). No relevant plateau in a CoF of a 0.1 – 0.2 can be seen, and the maximum test cycle duration until a CoF of 0.4 is reduced massively to ~1,400 cycles.

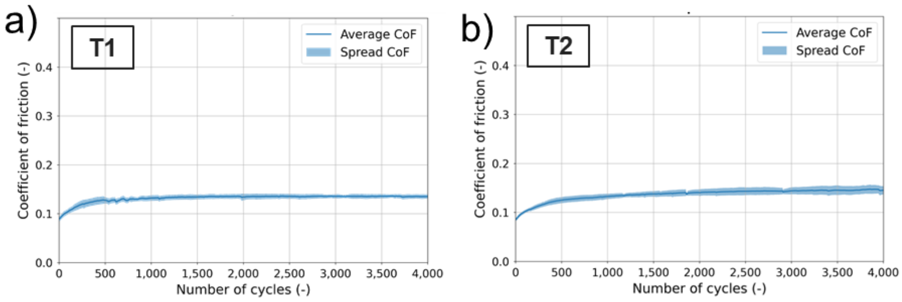

Figure 4: Friction graphs of twin-disc tests under simulated winter conditions at humidity of 60%: (a) T1: -10°C, (b) T2: 0°C.

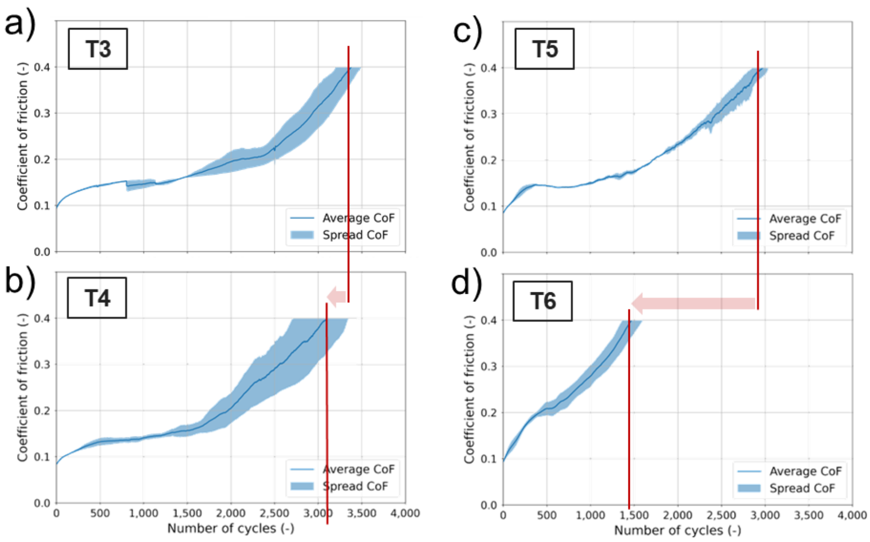

Figure 5: Twin disc test results under various summer conditions (temperature / humidity): (a) 15°C / 60 %, (b) 25°C / 60 %, (c) 35°C / 60 %, (d) 30°C / 25 %.

Similar CoF characteristic to the winter condition tests with low and stable values over the entire test duration of 4,000 cycles is observed at tests performed with high humidity of 90 % (Figure 6a and b). In contrast to the cold temperature tests, the tests *T7* and *T8* at 25°C and 35°C respectively exhibit slightly lower CoF values with ~0.12.

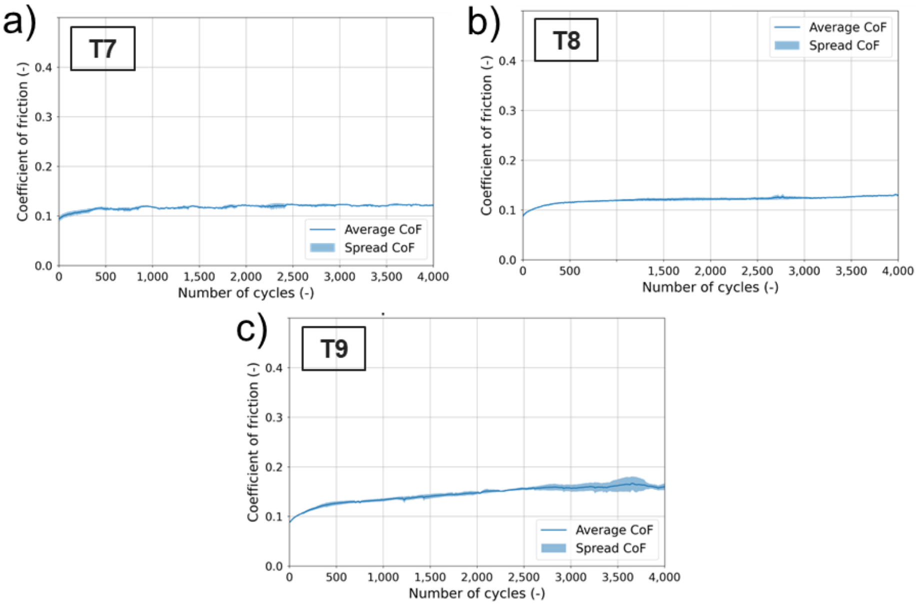

Figure 6: CoF graphs of twin disc tests with high humidity (90 %) at (a) 25°C and (b) 35°C. A water film in the contact and 0°C simulates slight snow fall (c).

4 Conclusions and Contributions

The results demonstratively show the impact of changing weather conditions on the performance of oil-based TOR-FM by sophisticated climate chamber setup in a high-load twin disc test. At simulated (dry) winter conditions low and stable CoF is observed (Figure 4), interpreted by an increased viscosity at low temperatures and therefore more persistent lubricating film within the wheel-rail contact. In addition, decreased temperature mitigates the degradation of solid additives [24]. Test results proof the effect of low temperature, since humidity was set to a medium humidity level of 60 % to ensure negligible water condensation along the contact band. Based on these results, focussing on the retentivity of TOR-FM product and its CoF characteristics, it is expected that at low ambient temperatures the amount of TOR-FM can be significantly reduced in comparison to summer conditions. This can reduce costs, impact on the environment and the risk of over-lubrication, hence, traction and braking problems. Comparable CoF characteristics are observed at humid conditions (Figure 6a and b) but higher temperatures. At 90 % humidity the air near the sample surface becomes saturated with moisture and with a surface temperature below the dew point, water vapor from the air condenses. For tests *T7* and *T8* this is the case with ambient temperature of 25°C and 35°C and – based on Magnus formula – 23.2°C and 33.1°C dew point temperature respectively. The lowest CoF with values of ~0.12 are observed, verifying the procedure of metre gauge railways in Switzerland to shut down TOR-FM application at humidities over 80 % to prevent traction difficulties. Similar situation occurs at “light snow” simulated at 0°C with water film after the application of TOR-FM along the circumference of the rail disc during the twin disc tests (Figure 6c). It must be noted that wet/snowy conditions at temperatures less or equal the freezing point are not the focus of the current work, and interaction of different elements such as base oil and solid lubricants of TOR-FM products, water and ice crystal lead to a very complex lubricant film state. This work put a focus on the critical setup to systematically studying various weather and climate conditions since this is often missing in available literature about testing TOR-FMs under various environmental conditions but plays a crucial role in interpreting the results. To ensure correct stated temperature and humidity values, a sensor placement as close to the wheel-rail contact as possible is crucial. However, many research works do not consider this critical topic. To guarantee correct data, the setup in the constructed climate chamber involves temperature and humidity sensors at both sides of the wheel-rail contact (Figure 2b). Further, the inlet positions of heat and humidified air are pivotal. Only a well-established climate chamber construction in combination with well-placed sensors can give reasonable results for systematic studies. Figure 7 demonstrate this issue; Setup 1 shows the configuration of heat inlet, humidity inlet, and sensor (temperature, humidity) positioning elaborated within this study (Figure 7a). When setting the environmental conditions to a temperature of 50°C and the humidity to 90 %, based on the values given by the sensors, a low and stable CoF of friction curve of ~0.12 results (Figure 7b). The high humidity is present at the wheel-rail contact area, hence, low CoF is dominating. However, when heat inlet, humidity inlet, and sensor positioning is considered less carefully, the same sensor values (50°C, 60%) lead to completely different CoF graphs (Figure 7b), as demonstrated by Setup 2 (Figure 7c). In this configuration, the humified air do not reach the actual wheel-rail contact position, therefore, the increased temperature is causing a steadily raising CoF, establishing dry contact situation with a CoF of 0.4 after ~2,100 cycles.

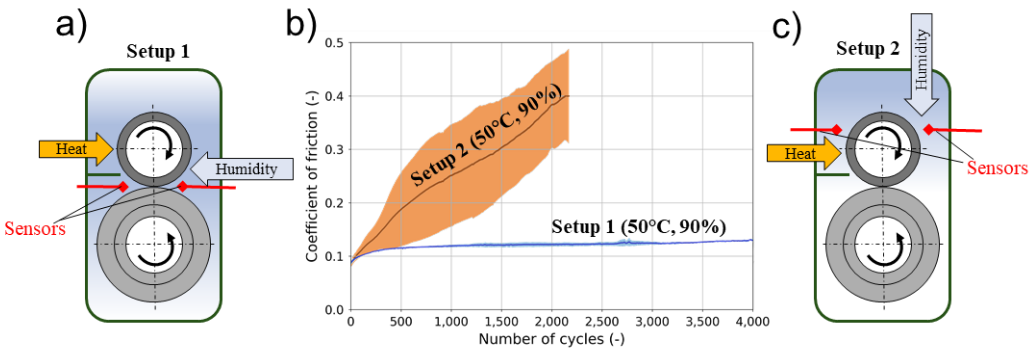

Figure 7: Demonstrating the importance of well-considered heat and humidity inlets, as well as sensor positioning: (a) Setup 1 ensures correct temperature and humidity at the wheel-rail contact, resulting in a low and stable CoF curve (b) based on high humidity. (c) In contrast, Setup 2 do not exhibit the correct temperature and humidity at the wheel-rail contact, besides measuring equal values compared to Setup 1.

With the correct setup, the tests deliver CoF graphs with low scattering and pronounced effects of changing environmental situations. The latter is nicely shown by the test results at summer conditions, where the increase of temperature (15°C to 35°C) at same humidity shows a decrease of number of cycles reached until the CoF is 0.4 (Figure 5a-c). This assumes that TOR-FM application is necessary more frequently with rising ambient temperature. However, this effect is intensified with decreasing humidity (Figure 5d). Results indicate that humidity changes are more significant to the performance of TOR-FM with respect to retentivity and CoF characteristics than temperature changes. In terms of railway safety, the strategy of Swiss metre gauge railways to automatically switch off TOR-FM application when humidity exceeds 80 % is validated by the test results of this work. However, well-developed climate chamber setups in high-load twin disc test rigs pave the way for closer meshed examinations around this threshold value to optimize railway efficiency. Further, the tremendous effect of low humidity is currently not considered in the field. Based on the experimental work, strategies of more frequent TOR-FM application and/or higher applied amounts at decreasing humidities and high temperatures can help minimizing wear of wheels and rails as well as mitigate potential noise emission.

The work demonstrates the relevance of changing weather and climate conditions on the CoF behaviour of oil-based TOR-FMs. The following main conclusions are stated:

- Low temperatures (0°C and below) and high humidity (90 %) reveal low and stable CoF (0.10 – 0.15) for the entire test duration of 4,000 cycles.
- Increasing temperatures (15°C – 35°C) decrease the number of cycles upon a CoF of 0.4.
- Decreasing humidity (at high temperatures) massively decreases the durability.

A well-developed climate chamber setup is crucial for reasonable results enabling systematic laboratory testing to help railways to optimize friction management strategies under challenging environmental conditions.

Acknowledgements

This work was carried out as part of the COMET Centre InTribology (FFG no. 906860), a project of the “Excellence Centre for Tribology” (AC2T research GmbH). InTribology is funded within the COMET – Competence Centres for Excellent Technologies Programme by the federal ministries BMIMI and BMWET as well as the federal states of Niederösterreich and Vorarlberg based on financial support from the project partners involved. COMET is managed by The Austrian Research Promotion Agency (FFG).

References

[1]C. T. Foo, B. Omar, and A. S. Jalil, “A review on recent wheel/rail interface friction management,” *J. Phys.: Conf. Ser.*, vol. 1049, p. 012009, July 2018, doi: 10.1088/1742-6596/1049/1/012009.

[2]M. Harmon and R. Lewis, “Review of top of rail friction modifier tribology,” *Tribology - Materials, Surfaces & Interfaces*, vol. 10, no. 3, pp. 150–162, July 2016, doi: 10.1080/17515831.2016.1216265.
[3]D. T. Eadie, M. Santoro, and J. Kalousek, “Railway noise and the effect of top of rail liquid friction modifiers: changes in sound and vibration spectral distributions in curves,” *Wear*, vol. 258, no. 7–8, pp. 1148–1155, Mar. 2005, doi: 10.1016/j.wear.2004.03.061.
[4]M. O. Folorunso, R. Lewis, and 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*, vol. 237, no. 8, pp. 1009–1024, Sept. 2023, doi: 10.1177/09544097221148236.
[5]M. Shen *et al.*, “Role of ambient temperature in the adhesion and damage characteristics of wheel/rail interface during rolling-sliding contact,” *Wear*, vol. 506–507, p. 204458, Oct. 2022, doi: 10.1016/j.wear.2022.204458.
[6]K. Rong, Y. Xiao, M. Shen, H. Zhao, W.-J. Wang, and G. Xiong, “Influence of ambient humidity on the adhesion and damage behavior of wheel–rail interface under hot weather condition,” *Wear*, vol. 486–487, p. 204091, Dec. 2021, doi: 10.1016/j.wear.2021.204091.
[7]L. B. Shi, L. Ma, J. Guo, Q. Y. Liu, Z. R. Zhou, and W. J. Wang, “Influence of low temperature environment on the adhesion characteristics of wheel-rail contact,” *Tribology International*, vol. 127, pp. 59–68, Nov. 2018, doi: 10.1016/j.triboint.2018.05.037.
[8]Y. Zhu, Y. Lyu, and U. Olofsson, “Mapping the friction between railway wheels and rails focusing on environmental conditions,” *Wear*, vol. 324–325, pp. 122–128, Feb. 2015, doi: 10.1016/j.wear.2014.12.028.
[9]E. E. Magel, “A Survey of Wheel/Rail Friction”.
[10] J. X. Li *et al.*, “Wear and damage behaviours of wheel and rail materials: Effects of friction modifier and environmental temperature,” *Wear*, vol. 523, p. 204796, June 2023, doi: 10.1016/j.wear.2023.204796.
[11] S. R. Lewis, R. Lewis, U. Olofsson, D. T. Eadie, J. Cotter, and X. Lu, “Effect of humidity, temperature and railhead contamination on the performance of friction modifiers: Pin-on-disk study,” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 227, no. 2, pp. 115–127, Mar. 2013, doi: 10.1177/0954409712452239.
[12] S. Skurka *et al.*, “The performance of top-of-rail products under water contamination,” *Tribology International*, vol. 188, p. 108872, Oct. 2023, doi: 10.1016/j.triboint.2023.108872.
[13] R. Galas, M. Omasta, I. Krupka, and M. Hartl, “Laboratory investigation of ability of oil-based friction modifiers to control adhesion at wheel-rail interface,” *Wear*, vol. 368–369, pp. 230–238, Dec. 2016, doi: 10.1016/j.wear.2016.09.015.
[14] R. Galas, M. Omasta, M. Klapka, S. Kaewunruen, I. Krupka, and M. Hartl, “Case Study: the Influence of Oil-based Friction Modifier Quantity on Tram Braking Distance and Noise,” *Tribol. Ind.*, vol. 39, no. 2, pp. 198–206, June 2017, doi: 10.24874/ti.2017.39.02.06.

[15] B. White, Z. S. Lee, and R. Lewis, “Towards a Standard Approach for the Twin Disc Testing of Top-Of Rail Friction Management Products,” *Lubricants*, vol. 10, no. 6, p. 124, June 2022, doi: 10.3390/lubricants10060124.
[16] B. White, R. Lewis, D. Fletcher, T. Harrison, P. Hubbard, and C. Ward, “Rail-wheel friction quantification and its variability under lab and field trial conditions,” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 238, no. 5, pp. 569–579, May 2024, doi: 10.1177/09544097231209483.
[17] S. R. Lewis, R. Lewis, G. Evans, and L. E. Buckley-Johnstone, “Assessment of railway curve lubricant performance using a twin-disc tester,” *Wear*, vol. 314, no. 1–2, pp. 205–212, June 2014, doi: 10.1016/j.wear.2013.11.033.
[18] J. C. Sánchez, J. A. Jaramillo, J. F. Santa, and A. Toro, “TWIN-DISC ASSESSMENT OF THE EFFECT OF TOP-OF-RAIL FRICTION MODIFIERS ON THE TRIBOLOGICAL RESPONSE OF ER8-R370HT PAIRS FOR USE IN WHEEL-RAIL SYSTEMS”.
[19] Y. L. Xavier, A. B. Rezende, S. T. Fonseca, E. Jun Kina, and P. R. Mei, “Study of the Initial Cycles Number Influence on the Retentivity of a Commercial Friction Modifier Using the Twin-disk Test,” *Tribology Transactions*, pp. 1–10, Feb. 2024, doi: 10.1080/10402004.2024.2311719.
[20] L. Buckley-Johnstone, M. Harmon, R. Lewis, C. Hardwick, and R. Stock, “A comparison of friction modifier performance using two laboratory test scales,” *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 233, no. 2, pp. 201–210, Feb. 2019, doi: 10.1177/0954409718787045.
[21] J.-W. Seo, H.-K. Jun, S.-J. Kwon, and D.-H. Lee, “Effect of Friction Modifier on Rolling Contact Fatigue and Wear of Wheel and Rail Materials,” *Tribology Transactions*, vol. 61, no. 1, pp. 19–30, Jan. 2018, doi: 10.1080/10402004.2016.1271487.
[22] “https://www.meteoswiss.admin.ch/climate/the-climate-of-switzerland.html.”
[23] B. White, Z. S. Lee, and R. Lewis, “Towards a Standard Approach for the Twin Disc Testing of Top-Of Rail Friction Management Products,” *Lubricants*, vol. 10, no. 6, p. 124, June 2022, doi: 10.3390/lubricants10060124.
[24] R. Kumar, I. Hussainova, R. Rahmani, and M. Antonov, “Solid Lubrication at High-Temperatures—A Review,” *Materials*, vol. 15, no. 5, p. 1695, Feb. 2022, doi: 10.3390/ma15051695.