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An Experimental Approach for Investigating Wheel-Rail Friction Behaviour in the Laboratory

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Abstract

This paper presents a laboratory-based experimental setup combining a contact simulator with the BUT rail tribometer. The contact simulator enables the formation of representative third-body layers on real rail segments, while the tribometer allows detailed characterization of traction behaviour and measurement of creep curves.

The capabilities of the proposed setup are demonstrated through three case studies addressing major friction regimes: low adhesion caused by leaf contamination, intermediate friction levels associated with top-of-rail (TOR) lubricants, and dry conditions. The first case study investigates the formation and frictional properties of leaf layers and residual leaf layers. The second evaluates the carry distance and retentivity of a commercial TOR lubricant under conditions representative of real railway operation. The third examines the evolution of frictional properties with increasing numbers of passes.

The results show that the proposed setup enables systematic laboratory investigation of friction layers that are otherwise difficult to study in the field. By bridging the gap between simplified laboratory tests and costly, variable field experiments, the setup provides a practical tool for evaluating friction management strategies and supporting the development of adhesion control solutions in railway systems.

Keywords: Portable tribometer, leaf contamination, top-of-rail lubricant, wheel–rail contact, carry distance, retentivity

1 Introduction

Frictional properties in wheel–rail contact are crucial for reliable railway operation. They vary significantly and are influenced by many factors, such as weather conditions [1] and the presence of leaves [2]. In addition, certain substances are intentionally applied to the contact interface. These include traction enhancers (e.g., sand) to overcome low adhesion, lubricants to reduce the coefficient of friction, and top-of-rail (TOR) products designed to maintain an intermediate level of friction on the rail head [3]. These approaches represent the main areas of friction management, which are further addressed in this paper.

The above-mentioned aspects are traditionally investigated through field and laboratory experiments. Field tests provide realistic results but are expensive, time-consuming, and subject to significant variability in operating conditions [4]. In contrast, laboratory experiments are less costly and offer well-controlled environments; however, their results are often difficult to transfer to real operating conditions [5]. Several types of small-scale tribometers are commonly used, including pin-on-disc [5], ball-on-disc [6], and twin-disc devices [7]. However, their configurations differ substantially from actual wheel–rail contact. Therefore, full-scale test rigs [8] and devices utilizing real rails [9], [10] have been developed to enable the formation of realistic third body layers and to study phenomena such as lubricant redistribution under laboratory conditions.

This paper presents an experimental setup that enables the evaluation of a wide range of frictional conditions, from ultra-low friction caused by leaf contamination, through intermediate levels targeted by TOR products, to dry contact conditions. A contact simulator [10] was used to form representative third body layers, which were subsequently evaluated using the BUT rail tribometer [11]. In total, three case studies addressing the above-mentioned friction regimes were conducted.

2 Methods

This study is based on a combined experimental approach integrating controlled layer formation and subsequent friction evaluation. The layers were generated on real rail segments using a contact simulator and frictional properties including creep curves were assessed using BUT rail tribometer. The capabilities of the setup were demonstrated through three case studies addressing major friction regimes: low, intermediate, and dry adhesion.

The first case study was focused on the preparation and characterization of leaf-derived low-adhesion layers. The second case study focused on the assessment of performance parameters of TOR lubricants, namely carry distance and retentivity. Carry distance refers to the distance between the application point and the location where the influence of the TOR product becomes negligible, whereas retentivity describes the number of wheel passes during which the product remains effective [10]. The third case study examined the evolution of frictional properties with increasing numbers of passes, referred to as cleaning effect.

2.1 Experimental devices

The contact simulator (see Figure 1, left) consists of three interchangeable one-meter-long S49 rail segments (total length 3 m) mounted in a rigid frame and a bearing steel wheel with a diameter of 150 mm. The wheel is pressed against the rail by a spring, generating a contact pressure of 0.7 GPa, and is driven by a stepper motor with a planetary gearbox. The wheel rolls along the rail at a speed of 0.2 m/s with a constant creep of 1.67%, which is ensured by a pinion mounted at the end of the shaft and engaging with a toothed rack on the frame. The device closely reproduces conditions in actual wheel–rail contact, with only the wheel being scaled. Therefore, it was used to run-in the rail and to form representative third-body layers. For more information see [10].

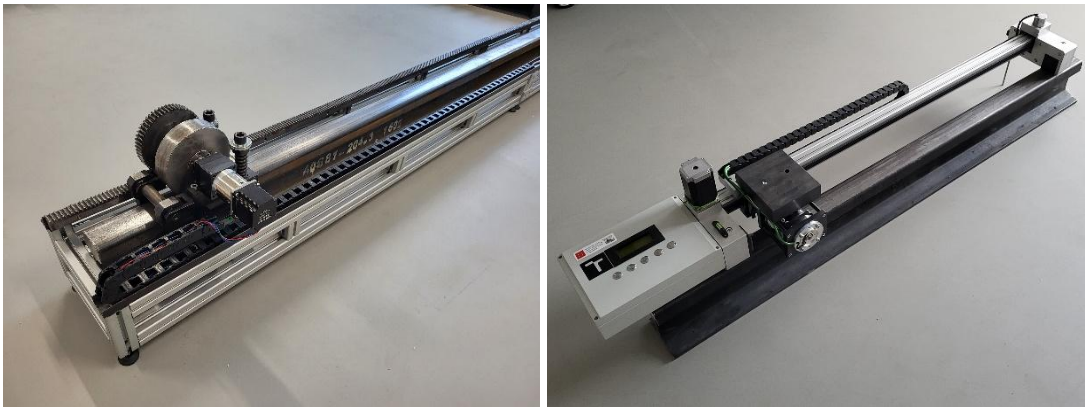

Figure 1: Contact simulator (left), BUT rail tribometer (right)

The BUT rail tribometer (see Figure 1, right) operates in a traction regime representative of wheel–rail contact conditions. Traction is generated by controlled braking of the measuring wheel, while the resulting creep depends on the frictional properties of the contact. The normal load is provided by the weight of the measuring module, producing contact pressures of 0.9 GPa. The device operates in three modes: constant, pulse, and ramp, which differ in the applied braking torque profile.

The device consists of a horizontal linear guide with a stepper motor-driven carriage carrying the measuring module. The system is fixed to the rail using magnetic-base blocks. A wedge mechanism allows adjustment of the wheel position between 0 and 8 mm. The measuring module integrates a wheel, encoder, magnetic friction brake, and torque transducer.

During measurement passes, braking torque is applied to the wheel, while creep is not actively controlled and develops naturally in response to the applied torque and contact conditions, similar to real wheel–rail interactions. Creep values are calculated from encoder data (Eq. 1), and the CoT is derived from the measured normal force (Q) and torque (M_B) (Eqs. 2–3). This procedure allows the generation of a complete creep curve in form of point cloud. It can be further fitted by a creep curve model e.g. Polach's model [12] or modified FASTSIM [13]. Another approach is to evaluate median CoT_1 and CoT_2 within creep bands 5-20% and 60-90%, respectively. It is simpler approach, but it still provides information about creep curve trend after saturation point. For more information see [11].

$$creep = \frac{v_L - v_R}{v_L} \cdot 100\% \quad (1)$$

$$T = \frac{2}{D}(I\alpha + M_B) \quad (2)$$

$$CoT = \frac{T}{Q} \quad (3)$$

where v_L and v_R represent the longitudinal speeds of the measuring module and measuring wheel, respectively; I is the inertia moment, α is the angular acceleration, and T is the traction force.

2.2 Case study 1 – leaf contamination

The first case study was based on [14] and investigated the formation of leaf layers on the rail. Three experiments were conducted to assess the effect of single and double leaf layers, as well as the behaviour of the residual leaf layer. Each experiment began with cleaning all contact surfaces using acetone, followed by a run-in process of 80 passes of the contact simulator wheel over one meter of rail at 0.7 GPa to stabilize CoT. Maple leaves soaked in water for 14 days were then applied over a 0.5 m section. In the first experiment, a single layer was tested; in the second and third experiments, two layers were applied, with the leaves removed in the third to examine the residual layer. The leaves were run in with 20 passes of the BUT rail tribometer, after which the measuring wheel was wiped with dry tissue. Measurements consisted of 20 passes in ramp mode at 0.9 GPa, and friction properties were evaluated in two creep bands: 5–20% and 60–90%. Test conditions are summarized in Table 1.

Test NO.	Number of layers of leaves	Run-in passes	Surface Condition
1	1	20	Leaf layer
2	2	20	Leaf layer
3	2	20	Residual layer

Table 1: Overview of experimental conditions used in case study 1

2.3 Case study 2 – performance parameters of TOR lubricant

The second case study inspired by [10] assessed the performance of a commercial TOR lubricant in conditions representative of actual wheel–rail contact. The contact simulator was used to form a representative layer of TOR lubricant, and CoT was measured with the BUT rail tribometer. The main performance parameters are carry distance and retentivity, which were evaluated in two separate experiments. Prior to testing, rail segments were cleaned with acetone and run in with multiple passes until CoT stabilized at dry-contact values (0.4–0.6), checked every 20 passes. Once stabilized, 80 µl of TOR lubricant was applied using a micropipette. The lubricant consists of biodegradable ester oil with thickener and soft metal particles (NLGI 0).

For the carry distance test, the lubricant was spread along the rail by the simulator wheel, creating imprints. The wheel was then moved back, transferring the lubricant further. No additional lubricant was added. Imprints were analysed with six tribometer measurement passes in ramp mode, with measurements taken every fourth imprint. The test ended when CoT_1 or CoT_2 exceeded 0.4, corresponding to dry conditions.

For the retentivity test, only the initial imprint (application point) was analysed. The wheel of contact simulator passed over the imprint, was cleaned, and the process repeated until CoT_1 or CoT_2 exceeded 0.4. Measurements were taken after 1, 10, 20, 30, and 60 passes. In this case, the creep curves represented as a point clouds were fitted using Polach model [12].

2.4 Case study 3 - cleaning effect

This case study focused on the cleaning effect in the laboratory. The BUT rail tribometer, operated at a contact pressure of 0.9 GPa, was used to assess the creep curve in a single pass and to condition the rail. Ramp mode was applied, with braking torque gradually increased to obtain the complete creep curve in each pass. The experiment began by cleaning the rail and measuring wheel with acetone to remove contaminants, followed by 40 measuring passes.

3 Results

3.1 Case study 1 – leaf contamination

Each measurement produced a creep curve, as shown in Figure 2, with each colour representing a single measuring pass. The left curve corresponds to dry conditions, and the right curve represents the leaf residue layer. Greater point scatter is observed for dry conditions, which may result from the dynamics of the measuring module and variations in friction along the rail. It should be noted that ramp mode was used, with parameters increasing between passes, causing the wheel to start sliding at different positions. Additionally, the cleaning effect investigated in Case Study 3 may contribute. The leaf residue layer substantially reduced friction, approaching the ultra-low zone [8] and provided more stable friction along the rail.

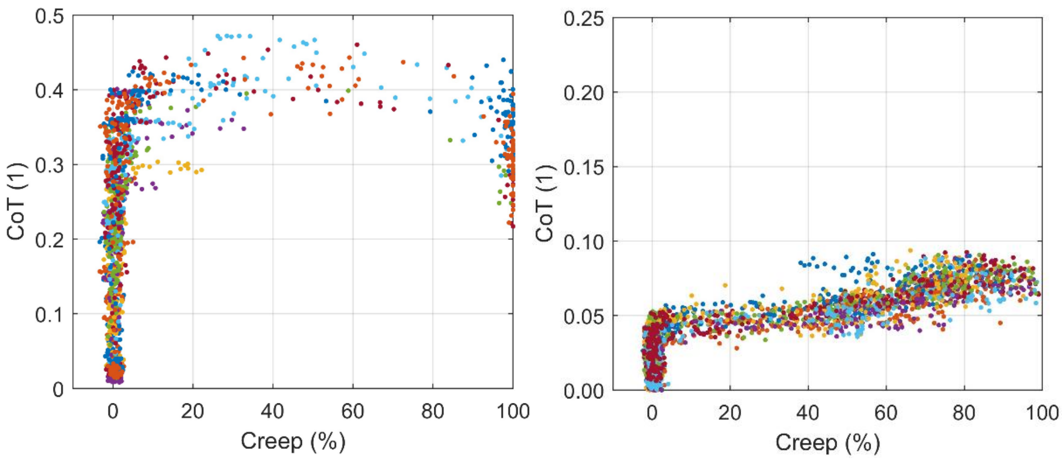

Figure 2: Creep curve for dry conditions (left) and leaf residue layer (right)

Dry conditions and the three leaf layers are compared in Figure 3. All leaf layers exhibit low and stable friction throughout the 20 measurement passes, indicating higher wear resistance. Among the leaf layers, Test 1 showed the highest CoT and interquartile range in both creep bands. In contrast, the leaf residue layer had the lowest CoT (0.046 in the low creep band and 0.064 in the high creep band) and the lowest interquartile range. In Test 1, no visible black layer formed in the contact path, although the leaf edges on the sides of the contact area turned black; low CoT was still achieved. In Test 2, with two leaf layers, a black, gel-like layer with a significant water content was observed and remained on the rail after leaf removal. These results suggest that the procedure in Test 3 produces the most consistent layer, suitable for further studies, such as adhesion restoration.

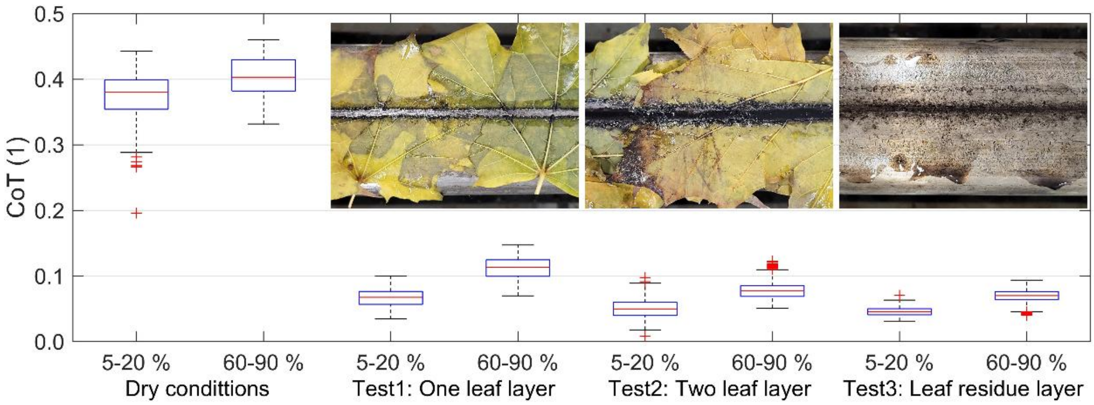

Figure 3: Comparison of frictional properties of three types of leaf layer

The main findings from the case studies indicate that laboratory-prepared leaf layers provide low CoT, with the lowest values observed for the leaf residue layer formed from two leaf layers after 20 passes at a contact pressure of 0.9 GPa. In addition, a reproducible methodology for preparing leaf layers was established, which can be further applied to studies of adhesion restoration materials.

3.2 Case study 2 – performance parameters of TOR lubricant

The carry distance of the TOR lubricant ranges from 12 to 16 imprints, as CoT2 exceeded 0.4 on the 16th imprint (Figure 4), a threshold representing dry conditions. The number of imprints can be converted to a realistic track distance based on the vehicle wheel diameter; for example, a wheel diameter of 666 mm corresponds to 25–33 m. This indicates a considerably shorter carry distance than typically claimed by manufacturers and aligns with findings reported in [15]. The lowest CoT is observed at the application point and gradually increases with each subsequent imprint, reflecting the progressive transfer of lubricant from the wheel to the rail.

The results of retentivity test are shown in Figure 5. The figure illustrates the evolution of creep curves during repeated passes of the contact simulator wheel over the initial imprint (application point). The lowest friction values were observed after the first pass and gradually increased with subsequent passes. In most cases, the trend of the creep curve is neutral or slightly positive. The TOR lubricant exhibited retentivity between 30 and 60 passes, as CoT exceeded 0.4 on the 60th pass. Retentivity can be understood as the number of wheelsets passing over the application point and also reflects lubricant consumption, providing guidance for the optimal application interval.

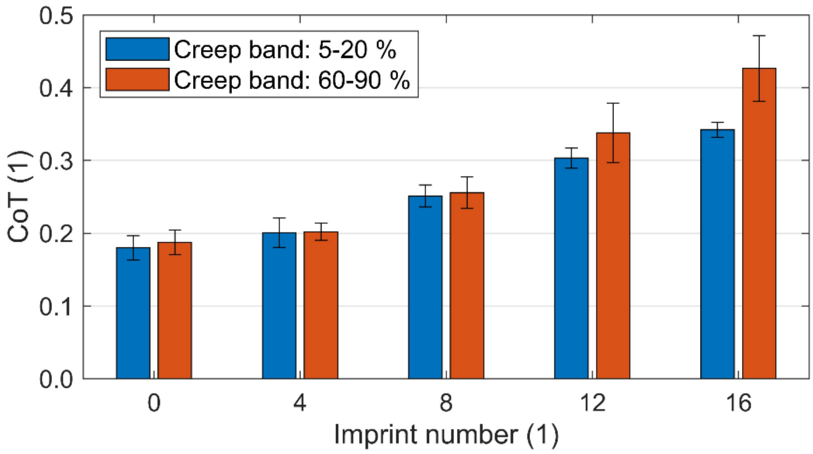

Figure 4: Carry distance of TOR lubricant

Overall, the combined use of the contact simulator and BUT rail tribometer provides a reliable setup for evaluating TOR lubricant performance under controlled laboratory conditions. The setup enables systematic assessment of friction evolution, carry distance, and retentivity, supporting the development of effective lubrication strategies for wheel–rail systems.

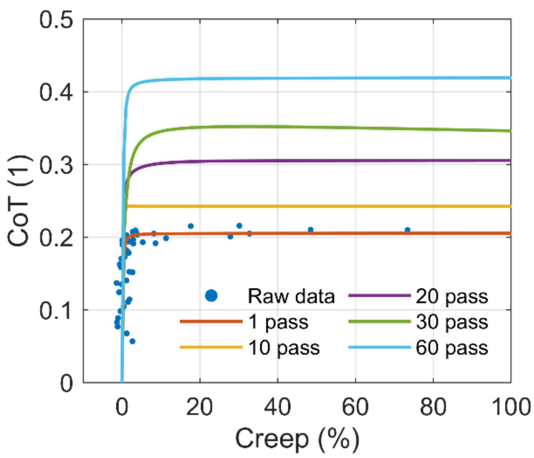

Figure 5: Development of creep curves during retentivity test

3.3 Case study 3 - cleaning effect

Figure 6 shows creep curves in point representation, with each measuring pass displayed in a different colour. During the first pass, CoT1 and CoT2 were around 0.016, while in the last pass CoT1 reached 0.35 and CoT2 0.38. The results indicate a gradual improvement in frictional properties over successive passes. High creep was observed in parts of some passes, typically toward the end.

This increase in CoT can be attributed to the work done by traction forces during each pass, which gradually improves friction conditions. This phenomenon has important implications: each subsequent wheelset experiences enhanced friction in the contact, allowing higher braking traction. In addition, this experimental approach can be used to study the wear resistance of third body layers.

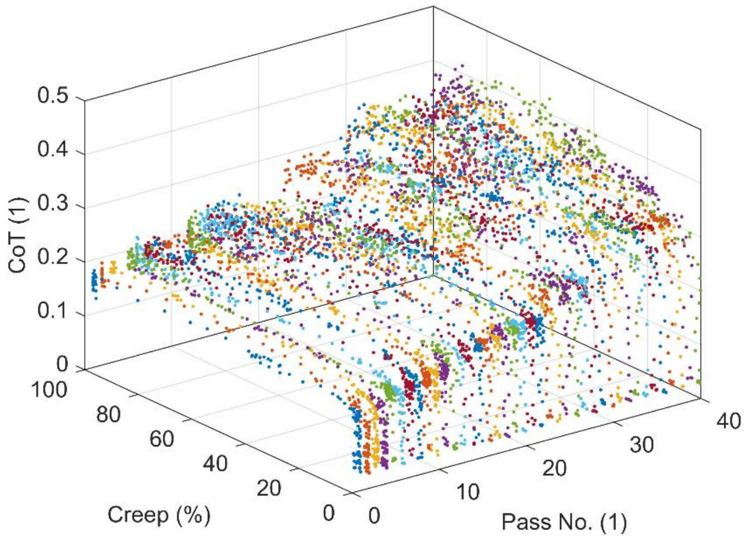

Figure 6: Evolution of creep curves with pass number

4 Conclusions and Contributions

This paper presents an experimental approach for investigating wheel–rail friction in the laboratory, using a rail contact simulator and a portable rail tribometer. The main contribution lies in the demonstrated capability of this combined experimental setup to generate, stabilise, and systematically evaluate representative third-body layers under controlled, application-relevant conditions.

The contact simulator forms friction layers on real rail segments through repeated rolling contact, producing surface states difficult to achieve with conventional small-scale tribometers, while the tribometer provides local, portable assessment of traction behaviour and creep curves directly relevant to wheel–rail interactions. Its portability allows consistent measurements in both laboratory and field conditions.

Together, the devices form an experimental setup bridging the gap between simplified laboratory tests and complex field measurements. The case studies demonstrate its use for various friction regimes, including low-adhesion layers, TOR lubricant performance, and friction evolution under repeated rolling contact. The setup can also be adapted to study adhesion-restoration materials, alternative lubrication strategies, or wear of friction layers.

Overall, the experimental setup provides a flexible and transferable basis for systematic investigation of wheel–rail friction, supporting both fundamental research and applied development of friction management solutions, as well as integration with modelling and digital twin approaches.

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