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Comparative Analysis of Dry and Water-Contaminated Twin-Disc Tests for Wheel–Rail Wear Assessment

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Abstract

Twin-disc testing is extensively employed to investigate the tribological behaviour of wheel-rail contacts under controlled laboratory conditions. Among the various operating environments explored in the literature, dry and water-contaminated contacts represent two fundamental reference cases for understanding friction and wear mechanisms in railway applications. Nevertheless, experimental results are often difficult to compare due to differences in testing methodologies, operating parameters and data reporting practices.

In this work, a focused comparative analysis of twin-disc experimental data obtained under dry and water-contaminated conditions is presented. Literature data were systematically collected by restricting the analysis to steady-state tests, allowing a coherent interpretation of friction coefficients and wear rates as functions of slip ratio and average traction stress. The results indicate that water contamination generally leads to a reduction in wear rate with respect to dry contact, particularly at low slip ratios. However, this beneficial effect progressively diminishes as slip increases, highlighting the dominant role of traction-controlled contact mechanics. A simplified predictive relationship based on the traction parameter is proposed for both dry and water-contaminated conditions, providing an interpretable framework for engineering applications.

Keywords: twin-disc testing, wheel–rail contact, dry contact, water contamination, friction, wear.

1 Introduction

The wheel–rail interface is one of the most critical elements of railway systems, directly influencing safety, energy efficiency and maintenance requirements. The interaction between wheel and rail surfaces is governed by complex tribological phenomena, where friction and wear result from the combined effects of contact pressure, material properties, creepage and environmental conditions. Understanding and controlling these phenomena is essential to ensure reliable operation while minimising maintenance costs and material degradation.

Experimental investigation of wheel–rail contact behaviour is traditionally performed using both full-scale tests [1-3] and laboratory-scale simulations [3-4]. While full-scale testing provides the most realistic representation of in-service conditions, it is often associated with high costs, limited controllability and long testing times. For these reasons, laboratory techniques such as twin-disc testing have become a widely accepted compromise, enabling systematic parametric studies under controlled and repeatable conditions.

Twin-disc tests allow the reproduction of rolling–sliding contact by independently controlling normal load, rolling speed and slip ratio. This makes them particularly suitable for studying the influence of specific parameters on friction and wear mechanisms. However, the extensive body of literature produced over the years has also introduced significant variability in testing configurations, contaminant application methods and data reporting approaches. As a result, direct comparison between different studies is often non-trivial and general conclusions may appear fragmented or inconsistent. Among the various environmental conditions investigated, dry and water-contaminated contacts represent two baseline cases of relevance. Dry contact conditions are commonly adopted as a reference scenario, providing insight into fundamental wear mechanisms and material response under severe adhesion-dominated contact. Water contamination, on the other hand, is frequently encountered in service during wet weather operation and is often assumed to act as a lubricant.

The objective of this paper is to provide a focused and coherent comparison between dry and water-contaminated twin-disc test results reported in the literature. By restricting the analysis to these two conditions and reinterpreting the data within a common framework based on traction stress, the work aims to clarify their respective influence on friction and wear behaviour and to support a more consistent interpretation of experimental results.

2 Materials and data selection

A systematic review of peer-reviewed literature was conducted to collect twin-disc experimental data relevant to dry and water-contaminated wheel-rail contacts. Only tests performed under steady-state conditions were considered, meaning that the operating parameters and contaminant conditions remained constant throughout the duration of the experiment. Tests involving transient phases, such as an initial dry run followed by the introduction of a contaminant, were excluded to avoid ambiguities in data interpretation.

The analysis was restricted to dry [5-27] and water-contaminated [5-7,17,28-29] conditions to ensure internal consistency and to enable a meaningful comparison between the two environments. For each selected test, key parameters describing contact mechanics and tribological response were collected. These included contact pressure, nominal contact area, slip ratio, traction force, coefficient of friction and wear rate. To facilitate comparison across different studies, wear rates reported in various forms were converted into a common normalised metric, accounting for sliding distance and contact area. When numerical values were not explicitly reported, data were extracted from published figures using digitalisation tools. Although this procedure introduces a degree of uncertainty, it allows the inclusion of a broader dataset and reflects common practice in literature-based meta-analyses. The traction parameter $T\gamma/A$, combining traction force T, slip ratio γ and contact area A, was adopted as a unifying variable to interpret wear behaviour. With respect to wear rate evaluation, some studies report only the total mass loss at the end of the test, while others express wear as mass loss per cycle (g/cycle) or as mass loss per unit distance and contact area (µg/m/mm²). When not directly provided and whenever feasible, wear data were converted into µg/m/mm² to ensure consistency with the graphical representations used in this work.

Out of a total of 496 records, 356 contacts correspond to line (cylindrical) contacts (71.6%), while 140 correspond to elliptical contacts (28.2%). Figure 1arepresents the probability distribution of the ratio between wheel hardness and rail hardness. Most of the data points are clustered between 0.8 and 1.2, indicating that most experimental studies utilize materials with similar hardness properties for both discs. Figure 1b shows the contact pressures vary between 500 MPa and 1500 MPa, with an average value of 1100 MPa and the exception of one study testing a contact pressure of 3000 MPa.

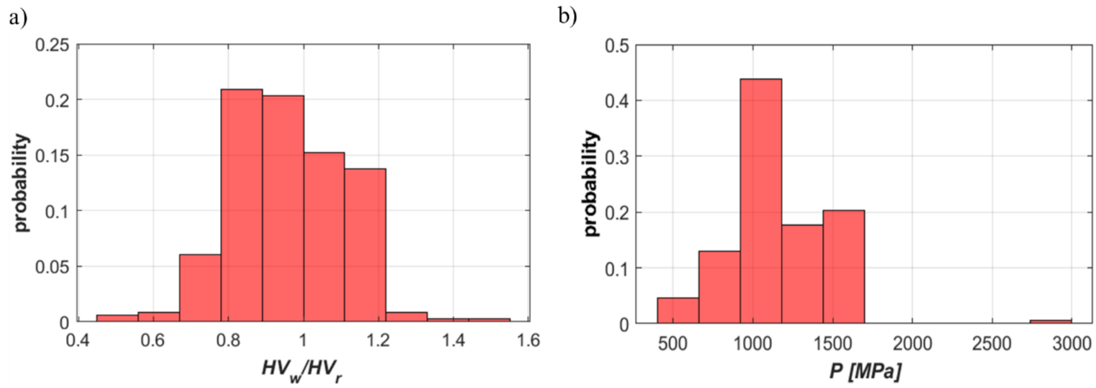

Figure 1: Distribution of experimental parameters collected from the literature: a) Ratio of wheel-to-rail hardness; b) Nominal contact pressure in MPa.

3 Results and discussion

The frictional response observed in twin-disc testing provides the primary key for interpreting wear evolution in wheel–rail contacts (Figure 2). For this reason, a unified analysis of friction behaviour under both dry and water-contaminated conditions is presented before discussing wear results. Under dry contact conditions, the coefficient of friction typically increases with slip ratio and sliding severity [3-4,]. At low slip values approaching pure rolling, friction coefficients generally remain below 0.3–0.4, indicating limited micro-slip and a predominantly rolling-driven contact regime. As slip ratio increases, friction progressively rises and stabilises in the range between 0.4 and 0.7 for most of the examined tests, with occasional values exceeding 0.8 under severe rolling–sliding conditions. This behaviour reflects the transition from a rolling-dominated regime to a sliding-dominated one, where adhesion and surface interaction between the contacting steels become increasingly significant [3,5,30-31]. The increase in friction with slip is consistent across different specimen geometries and material combinations, suggesting that frictional behaviour is mainly governed by contact mechanics rather than by specific material pairing. In particular, the evolution of friction directly controls the traction stress developed at the interface and therefore the mechanical energy dissipated within the contact. When water is introduced at the contact interface, a markedly different frictional response is observed, particularly at low and moderate slip ratios. In this regime, water generally reduces the coefficient of friction, often leading to values below 0.3. This reduction indicates that water acts as a partial lubricant, limiting direct asperity interaction and reducing adhesion between wheel and rail materials. The presence of a thin liquid layer modifies the contact conditions by decreasing the shear strength required to sustain rolling–sliding motion. However, the lubricating effect of water is strongly dependent on slip ratio. As slip increases, friction coefficients under water-contaminated conditions tend to rise and progressively approach those observed in dry contact.

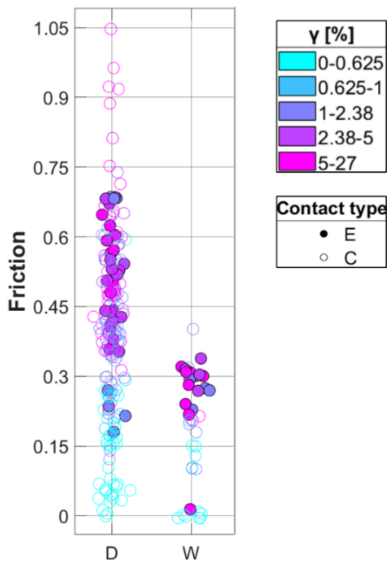

Figure 2: Comparison of measured friction coefficients for dry (D) and water-contaminated (W) conditions. Data points are coloured according to the slip ratio.

At high slip levels, the frictional response of wet contacts becomes comparable to that of dry contacts, indicating that the water film is no longer able to effectively separate the contacting surfaces. This transition can be attributed to the combined effects of increased shear stress, local heating and the expulsion of the liquid from the contact interface. The analysis also suggests that the influence of water flow rate on steady-state friction is limited. Once enough water is present within the contact, further increases in flow rate do not produce significant changes in friction coefficient. Instead, friction appears to be primarily controlled by slip ratio and contact severity. Overall, the comparison between dry and water-contaminated conditions highlights that water cannot be considered a fully effective lubricant in wheel–rail contacts. Rather, it behaves as a friction modifier whose effectiveness is restricted to a limited range of operating conditions characterised by low to moderate slip. As slip increases and the contact becomes more severe, frictional behaviour converges towards that observed under dry conditions, with direct consequences for wear evolution.

Dry contact tests constitute most available twin-disc experimental data (about 89%). When wear rate is plotted as a function of the traction parameter, a clear and consistent trend emerges across different studies (Figure 3).
The results show that wear rate increases with increasing traction stress, with slip ratio playing a dominant role in controlling material removal. At low slip values, close to pure rolling, wear remains limited even under relatively high contact pressures. As slip increases, a transition towards more severe wear regimes is observed, leading to a rapid rise in wear rate. Interestingly, wheel and rail specimens exhibit largely overlapping trends when analysed in terms of traction stress. This suggests that, under dry contact conditions, similar wear mechanisms may operate on both components when comparable contact mechanics are imposed. This observation reinforces the suitability of twin-disc testing for comparative studies aimed at balancing wheel and rail wear behaviour.

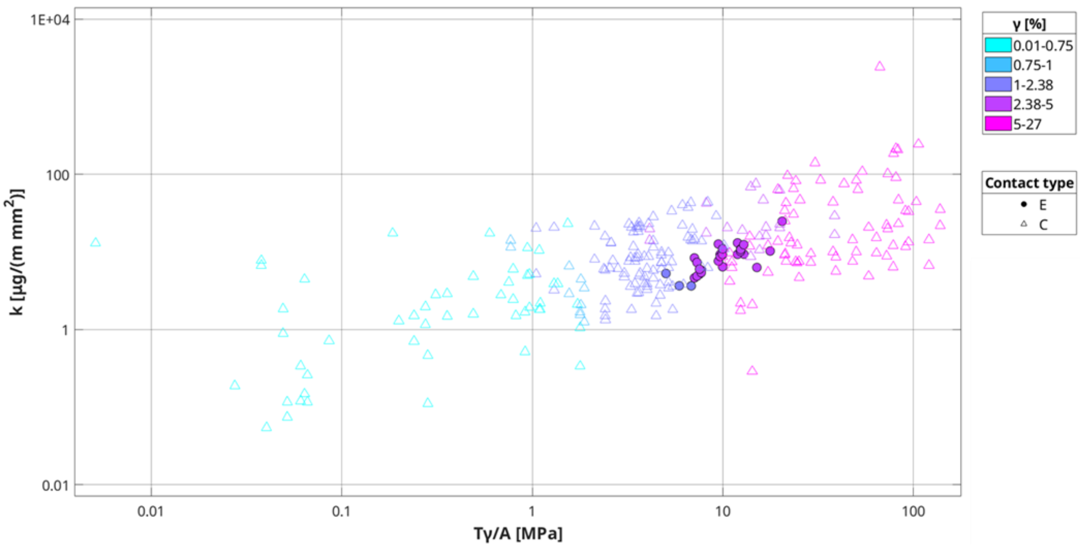

Figure 3: Wear rate as a function of *Tγ/A* parameter for dry tests.

The presence of water at the contact interface significantly alters the tribological response compared to dry conditions (Figure 4). At low and moderate slip ratios, water-contaminated tests generally exhibit lower wear rates, indicating a partial lubrication effect. This reduction in wear can be attributed to the ability of water to limit direct metal-to-metal contact, thereby reducing adhesion and surface damage. However, as slip ratio increases, the beneficial effect of water progressively diminishes. At higher slip values, wear rates approach those observed under dry conditions, suggesting a breakdown of the lubricating action. This behaviour can be explained by considering the contact mechanics under severe rolling–sliding conditions. At high slip, the contact interface experiences increased shear and local heating, reducing the effectiveness of the water film in separating the surfaces. Consequently, contact behaviour becomes increasingly governed by solid-to-solid interaction rather than fluid-mediated lubrication. Available data also indicate that water flow rate has a limited influence on wear rate compared to slip ratio and traction stress. Once a minimum amount of water is present at the contact, further increases in flow rate do not lead to a significant reduction in wear, highlighting the secondary role of this parameter.

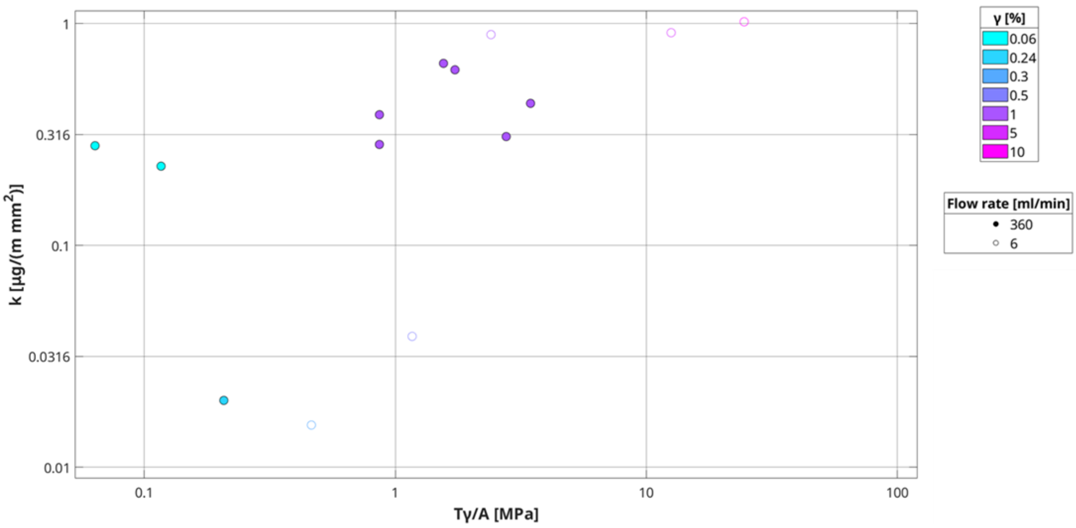

Figure 4: Wear rate as a function of $T\gamma/A$ parameter for water tests.

A direct comparison between dry and water-contaminated data provides further insight into the role of environmental conditions. For a given traction parameter, water contamination consistently results in lower wear rates at low slip ratios. However, the difference between the two conditions narrows as traction stress increases, eventually becoming negligible at high slip. This finding demonstrates that water should not be regarded as a universally effective lubricant in wheel–rail contacts, particularly in operating scenarios involving high creepage, such as acceleration or braking. These observations emphasise the importance of considering slip-dependent effects when interpreting water-contaminated twin-disc test results and when extrapolating laboratory findings to real operating conditions.

4 Predictive model

To support an engineering-oriented interpretation of the experimental trends, a simplified predictive relationship between wear rate and traction parameter is considered [4]:

$$\log_{10} k = a_1 \log_{10} \frac{T\gamma}{A} + a_{2,C} \tag{1}$$

where $k$is the specific wear rate and $a_{2,C}$accounts for the contact condition, namely dry or water-contaminated. This formulation captures the primary dependency of wear on traction stress while maintaining a limited number of parameters. The similarity of the slope for both conditions confirms that the underlying wear mechanisms are largely governed by slip-controlled traction, whereas the intercept reflects the mitigating effect of water at low traction levels [4,7]. The simplicity of this approach makes it particularly suitable for comparative analyses and preliminary test design, avoiding overfitting and enhancing physical interpretability. Figure 5 shows the scatter plot for the model with regression line and the confidence limit, while estimate and standard deviation of the parameters are reported in Table 1.

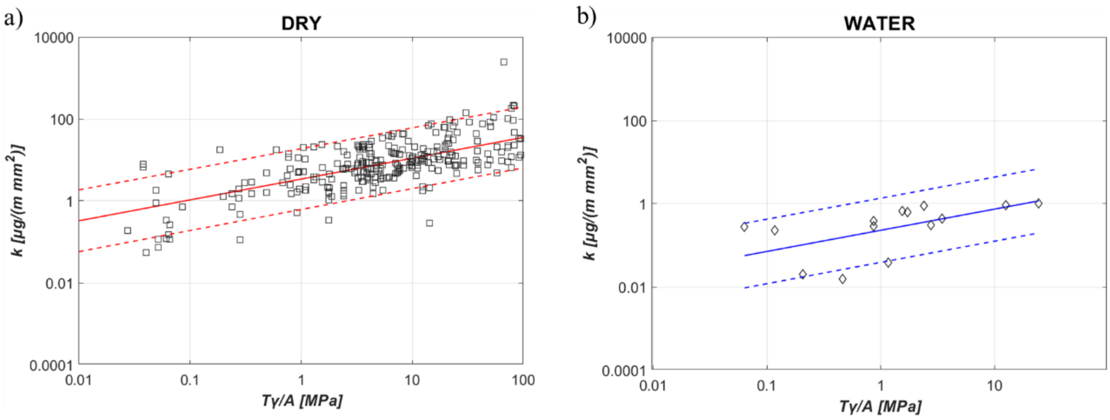

Figure 5: Linear regression analysis for dry tests (a) and water tests (b).

Parameter name	Estimate	Standard deviation
a_1	0.508	0.030
$a_{2,C,dry}$	0.531	0.035
$a_{2,C,water}$	-0.64	0.13

Table 1: Estimated values and standard deviations for the predictive model.

4 Conclusions and Contributions

A focused comparative analysis of dry and water-contaminated twin-disc test results has been presented. The main conclusions can be summarised as follows:

- Wear evolution in both dry and water-contaminated contacts is primarily governed by slip ratio and traction stress.
- Water contamination generally reduces wear at low slip ratios, but its lubricating effect diminishes as slip increases.
- At high traction levels, wear rates under water-contaminated conditions become comparable to those observed in dry contact.
- Water flow rate plays a secondary role compared to contact mechanics.
- A simplified traction-based predictive framework provides an effective and interpretable tool for comparing dry and water-contaminated test results.

Overall, the results contribute to a clearer and more consistent interpretation of twin-disc experiments and provide useful guidance for the design of laboratory tests representative of real wheel–rail operating conditions.

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