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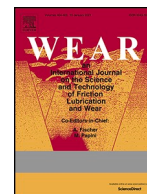
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Experimental characterization of the tribological behaviour of railway brake shoes with a scaled twin-disc rig

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ABSTRACT

European regulations are thrusting the replacement of traditional cast iron brake shoes with new composite materials, aiming to reduce rolling noise. Nonetheless, composite materials exhibit different tribological and thermal properties with respect to cast iron shoes. This paper aims to investigate and map the wear and frictional behaviour of a K-type composite shoe and compare it with a traditional cast iron shoe. Experimental tests are performed with a dedicated scaled twin-disc rig, which follows Pascal's similitude rule. Tests are run under drag braking conditions exploring a wide range of real-world speed and contact pressure conditions. The collected data is used to tune a power-law analytical model for the calculation of a proportionality coefficient, depending on speed and contact pressure, that relates the amount of worn material to the dissipated energy. The results of the experimental campaign show that the volume rate of the K-type material is approximately 10.5 times lower when compared to cast iron, hence improving the lifetime span of composite shoes. For both materials, the wear rate increases with increasing contact pressure, while an opposite behaviour is obtained with respect to speed: with increasing speed, wear of the cast iron shoe tends to decrease, while wear of the composite material becomes higher. Concerning friction, it is found that the composite material has a more stable behaviour with low dependency on speed and pressure, while the coefficient of friction of the cast iron shoe has a wider variation range.

1. Introduction

The mechanical braking system in railway vehicles primarily relies on the action of friction to dissipate the kinetic energy of the train into heat. In the case of tread braking, brake shoes are pressed directly against the wheel tread, generating the frictional force that produces the braking torque. To this end, the material used for the shoes should have an optimal coefficient of friction (COF), resist wear, produce a consistent braking effect, and reduce noise and particles emissions to a minimum. Originally, the material of choice was phosphorous cast iron (P10), which has good braking capabilities, but also presents several downsides, such as its high noise levels, the emission of iron oxides and pollutants [1–3], and its harshness on the wheel tread surface. To reduce the noise levels, the P10 shoes are progressively being replaced with new composite shoes, which contain organic and inorganic fibres. The composite materials currently in use are classified mainly based on their friction properties, and the most used are the LL shoes, that guarantee a COF similar to that of cast iron, and K shoes, that have high and stable values of COF, allowing to have a consistent braking effect [4–6].

Nonetheless, composite braking shoes have a reduced thermal conductivity compared to cast iron, which leads to a higher heat absorption by the wheel, increasing the thermal stresses it must sustain [7–9]. These materials have highly variable compositions and physical, thermal and mechanical properties, prompting the need to characterize them in a rapid, efficient, reliable and economic manner [10–14].

Furthermore, developing a predictive model for wear is crucial, since it allows to program maintenance and substitution intervals, reducing the need for inspections and unnecessary costs. In the railway field, much attention is paid to wear at the wheel-rail interface with several wear laws that can be implemented in dynamic simulation codes [15], and different parameters that are known to relate with the amount of worn mass [16]. Archard's wear law [17–19] correlates the normal force and the sliding distance to the volume of worn material, with a proportionality coefficient that depends on the wear regime, defined by pressure and slip velocity. The British Rail Research (BRR) [20] and Sheffield University (USFD) [21] wear functions are also widely employed, and they are based on an energetic approach, as they relate wear to the dissipated energy. Precisely, the BRR law relies on the wear

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number $T\gamma$, obtained from the tangential contact force between the bodies, which defines the wear regime. On the other hand, the USFD wear function accounts for the specific energy with respect to the contact surface area, since it is based on the wear index $T\gamma/A$. These methods are reliable ways to predict wear at the wheel-rail contact and have good accordance between each other [22]. On the other hand, they cannot be directly applied to describe the wear phenomenon during tread braking, as they consider contact between two components made of steel, with much lower relative velocities, subjected to higher contact pressures. Many studies, such as Enblom et al. [23], neglect the effect of tread braking when simulating the wear behaviour of railway vehicles wheels, although it has an important impact on the wheel wear phenomenon [24]. Hence, to study the wear phenomenon during braking, these existing models must be re-calibrated, or alternative models need to be developed.

Walia et al. [25] simulated the wear behaviour of cast iron and composite brake blocks, using Archard's model, and compared the results with experimental data, finding a good matching. According to the latter reference, the wear rate of cast iron was about 10 times higher than that of composite blocks. Wang et al. [26] developed a wheel wear prediction model, combining the effects of rail and an abrasive block, used to condition the tread surface. The wear losses coming from the two interactions were both modelled using Archard's law, and then the results were compared with experimental data, finding that taking into consideration the abrasive block increases the agreement between the model and the experimental tests.

Several studies were dedicated to characterising the tribological and wear characteristics of both cast iron and composite materials for brake blocks. Vakkalagadda et al. [27] compared the behaviour of cast iron, K-type and L-type blocks, finding that for both cast iron and L-type blocks the COF decreases as the braking force and velocity increase, while K-blocks exhibit an almost velocity-independent COF. The wear rate, calculated with respect to the dissipated energy, is much higher in cast iron than composite blocks. Similar results were found by Wang et al. [28] while comparing two different composite blocks materials. This study also highlights that the worn material increases as the COF increases. Ilanko et al. [29] investigated the wear behaviour of three fibre-reinforced composite materials for automotive disc brakes, that should substitute those containing asbestos, known for its toxicity, identifying which parameters had the highest influence on the mass loss. The study showed that both the normal force applied to the pad and the speed increase the COF, and therefore also the quantity of worn material. This work also differentiates between three wear regimes, namely mild, severe and ultra-severe, assessing that the mild regime is the only acceptable one in normal operating conditions. Lyu et al. [30] and Varriale et al. [31] conducted pin-on-disc tests to map the COF of composite materials against contact pressure and velocity, with similar results. Again, it is confirmed that the COF decreases with an increase of velocity and pressure, even though at high pressures the COF rises.

Following the previous research, the present paper aims to compare the wear behaviour and COF of P10 and K-type composite railway shoes, as well as to develop an empirical analytical model that allows to predict the global wear behaviour of both shoe materials. To do this, experimental tests were carried out on a scaled twin-disc rig, equipped with a scaled tread braking system, with one single block in 1Bg configuration. The test rig was designed according to Pascal's scaling rule [32,33], so that although geometrical sizes are reduced to one fifth, the velocity and pressure correspond to those of the full-scale system [34,35]. As a major novelty, the results obtained with this experimental setup allow to compare the materials in speed and pressure ranges that resemble those of real freight train operating conditions, which is not possible with smaller test rigs or pin-on-disc tests. The experimental campaign examined both materials, mapping wear as a function of speed and contact pressure under drag braking conditions, i.e., under braking at constant speed. Wear is quantified by measuring the global amount of mass loss in the shoes, allowing to compare the life expectancy of the

shoes, which impacts the maintenance costs. Furthermore, as a major contribution, this paper provides simple analytical expressions, fitted on the collected data, to calculate the wear coefficient as a function of speed and contact pressure. Such models could be easily integrated within common longitudinal train dynamics (LTD) codes to estimate the amount of worn material during specific train braking operations [36, 37]. However, the applicability of the proposed model in LTD codes is limited to drag-braking conditions consistent with the experimental setup, therefore its extension to stop-braking manoeuvres would require additional dedicated testing.

The main objective of this work is to compare the cast iron and K-type composite shoes on a macroscopic level, measuring volume lost due to wear during testing, that were conducted trying to mitigate most factors that could introduce variability between the two materials, such as the susceptibility of tribological properties to temperature. Although of course this analysis approximates the actual behaviour of the materials, it can still offer interesting results, especially to freight wagons owners, as it enables them to have a rough estimate of the life expectancy of the brake shoes. These subjects are usually not concerned with a detailed description of local wear mechanisms, but rather on the overall wear, since that has the highest impact on life expectancy and costs. The investigation of local degradation mechanisms, that can be strongly influenced by thermal effects and nonlinearities, as well as studies on microstructural behaviour, surface and debris analysis, are outside the scope of the present works and is demanded to future upgrades of the activity. Furthermore, the experimental campaign described in this paper only focuses on wear of the brake shoes, while wheel wear is not considered. In fact, the estimation of the amount of material worn from the wheel is more difficult to perform on the current bench setup, as it would require repeated mounting and dismounting of the wheel rim, with a long stretching of the experimental times. Therefore, the research group is currently designing a laser sensor system to extend the analysis to wheel wear in future upgrades of the activity.

The article is structured as follows. Section 2 provides a description of the test rig and of the acquisition system, along with the test setup, measured data and testing procedures, followed by the experimental data processing to calculate wear and friction coefficients. Section 3 presents the results, comparing those obtained for the cast iron and composite shoes at different speeds and pressures, and the respective empirical models achieved by fitting the data. Finally, the conclusions summarise the results and discuss future development for the research.

2. Material and methods

2.1. The scaled twin-disc test bench

Tests in the present paper were carried out using a novel scaled twin-disc test rig previously developed by the Politecnico di Torino (PoliTo) railway research group [34]. The CAD drawing of the test bench and the current setup of the test bench are shown in Fig. 1. Originally designed for wheel-rail contact wear tests only, the rig was later modified to accommodate tread braking tests [35], through the introduction of a specifically designed scaled tread braking system, see Fig. 2. With reference to Fig. 1, at the core of the test bench are two discs representing a railway wheel (1) and rail (2). Their geometries and profiles reproduce the real full-scale components, scaled by a factor of 5. Currently, the wheel profile is machined to the 1:5 scaled S1002 profile, while the rail profile is a 1:5 scaled version of the UIC60 profile, with a minor correction to compensate for the longitudinal curvature of the rail disc. Nonetheless, the wheel and rail disc configuration allows to test different profiles by simply replacing the outer rims fitted on a hub. The discs are pressed against each other by preloading two compression springs (3) with a threaded system. The stiffness of the helical springs was designed so that the resulting normal force at the contact interface between the discs remains virtually constant even after the discs wear out. Based on the type of test to be performed, each disc can be powered

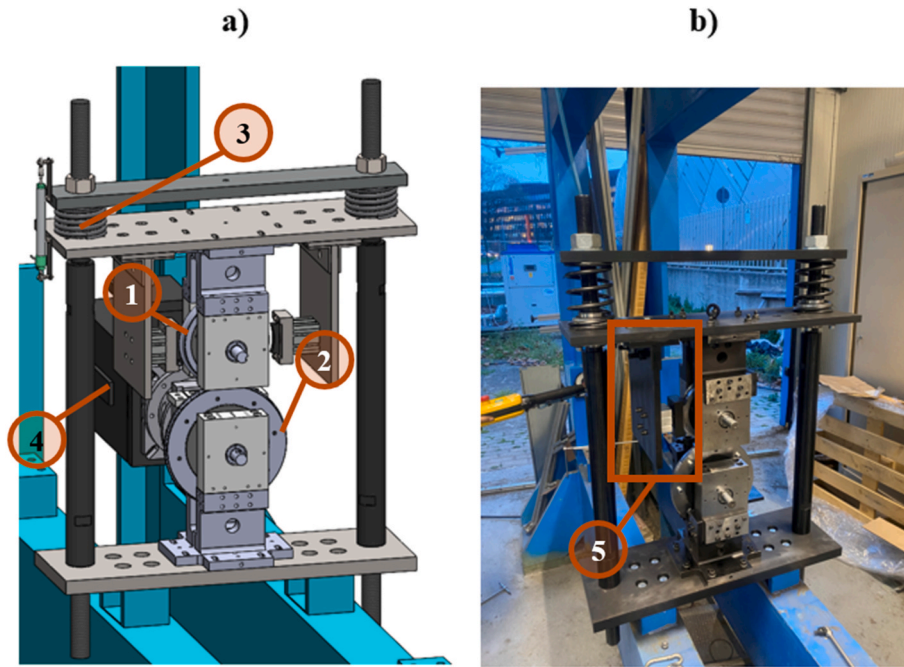


Fig. 1. (a) CAD model of the test bench. (b) Current setup of the test bench used in the current paper.

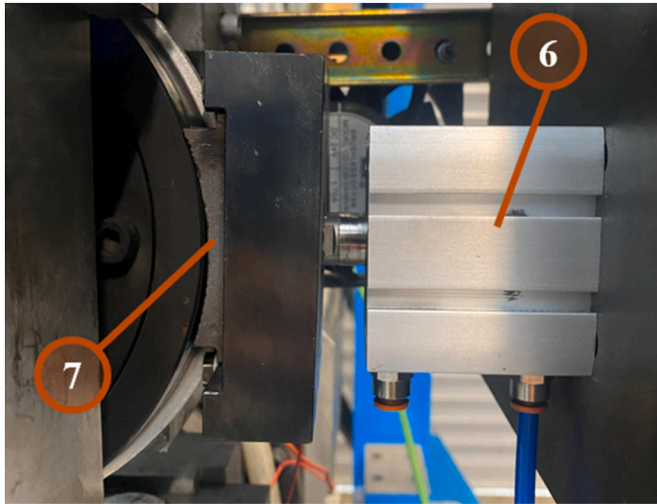


Fig. 2. Detail of the scaled tread braking system.

by a brushless motor (4). However, in the drag braking tests described in this paper, only the rail-disc is powered, while the wheel-disc is driven with minimum slip thanks to the high value of applied contact pressure between the two rollers.

The bench design follows Pascal's scaling strategy, ensuring that the contact pressure at the interface between the two discs corresponds to the actual conditions of wheel-rail contact of railway vehicles. The specific scaling factors are shown in Table 1, as a function of the length scaling factor φ_L which is equal to 5. The main bench design choices ensure that the data gathered from the bench can be closely correlated to real-life scenarios.

Fig. 2 shows a detailed view of the scaled tread braking system (5) mounted on the bench. Pneumatic cylinders (6) mounted on each side of the wheel-disc press a scaled brake shoe (7) against the wheel tread. The air supply to the cylinders is regulated by a solenoid proportional valve, allowing to accurately control the braking pressure. A more detailed description of the test bench and the design of its components is

Table 1

Scaling factors according to Pascal's similitude model.

Quantity	Scaling Factor
Length	φ_L
Density	1
Young's modulus	1
Contact Pressure	1
Area	φ_L^2
Time	φ_L
Speed	1
Acceleration	φ_L^{-1}
Mass	φ_L^3
Force	φ_L^2
Weight	φ_L^3

provided in Refs. [34,35].

2.2. Experimental tests

Before starting the experimental campaign, the braking system was calibrated. Concerning the braking system, since the proportional solenoid valve requires a voltage input in the 0–10 V range, while the data acquisition board outputs a maximum of 5 V, an amplification circuit was installed upstream of the valve. This circuit doubles the input voltage, allowing for higher braking pressures than those achieved in previous drag braking activities. Fig. 3 shows a diagram of the electrical and pneumatic circuit.

The calibration of the amplifying circuit involved verifying the input-output voltage relationship and confirming the doubling effect. After installation, a second calibration correlated the amplifier input voltage, controlling the proportional valve, with the force exerted by the pneumatic cylinder on the wheel. This was achieved using an ad-hoc LabVIEW programme: an input voltage was set, amplified, and sent to the valve, which actuated the cylinder to press a button load cell against the wheel tread. Air pressure was measured using a pressure transducer with digital output, and the load cell recorded force values at different values of input voltages and therefore pressures. From this calibration, the characteristic air pressure–braking force curve was obtained.

The main experimental campaign involved drag braking tests

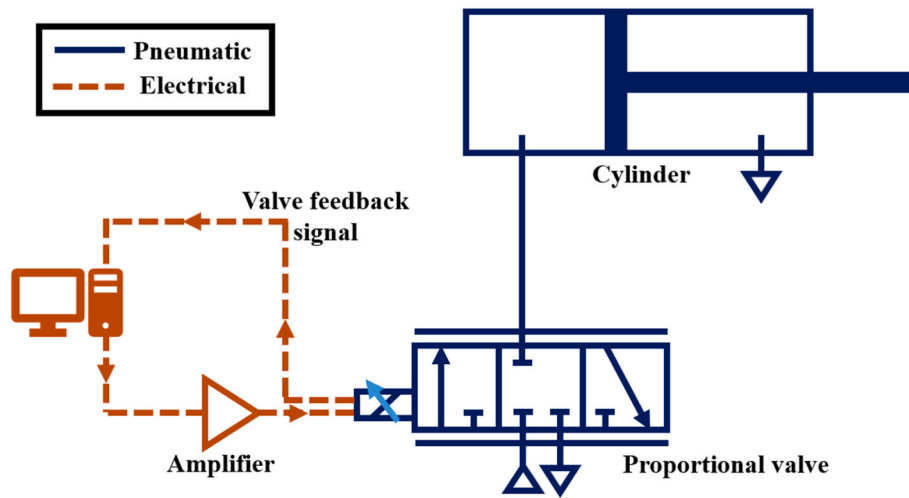


Fig. 3. Diagram of the brake system.

performed in a 1Bg configuration using the same brake shoe throughout. This configuration was specifically selected to make sure that all the dissipated power originates from the contact between the two components. This avoids uncertainties that would arise in 2Bg configuration, in case the two brake shoes had a slightly different behaviour.

During each test, a brake shoe was pressed against the wheel tread for a predefined duration and braking pressure with the wheel disc, driven by the rail disc, spinning at constant speed. The values of tested pressure and speed are comparable to real-world braking conditions and have nominally unitary scaling as prescribed by Pascal's similitude model, see Table 1. Table 2 contains a summary of the test programme and the duration of each test. The experimental campaign includes four speed levels (30 km/h, 50 km/h, 70 km/h, 90 km/h) and four brake shoe-wheel contact pressure levels (0.3 MPa, 0.6 MPa, 0.8 MPa, 1.2 MPa). These values span the typical speed range of freight wagons as well as the common range of applied contact pressure due to the pressing force on the brake blocks. In the experimental tests, drag braking operations were simulated on the scale bench to minimize transient effects and obtain wear rate under stable operating conditions. The reasons for choosing drag braking over other service braking operations are twofold. Firstly, European standards and technical specifications cite explicitly drag braking in the procedures for the characterisation of brake shoes. Additionally, other operations, such as stop braking, would introduce non-linear effects due to the thermal transient phenomenon, which cannot be reliably reproduced on the bench with Pascal's scaling rule. Drag braking allows a higher repeatability in testing conditions, which is preferable in order to have a fair comparison of the shoes properties. The investigation of wear rates under stop braking operations with dominating transient effects is demanded to future developments of the activity.

Two brake shoe materials were tested: a traditional phosphorus P10 cast iron and a commercial K-type composite; they are shown in Fig. 4. Both scaled shoe specimens were sourced from real full-scale brakes. The specific K-type composite shoe under test is commonly adopted by

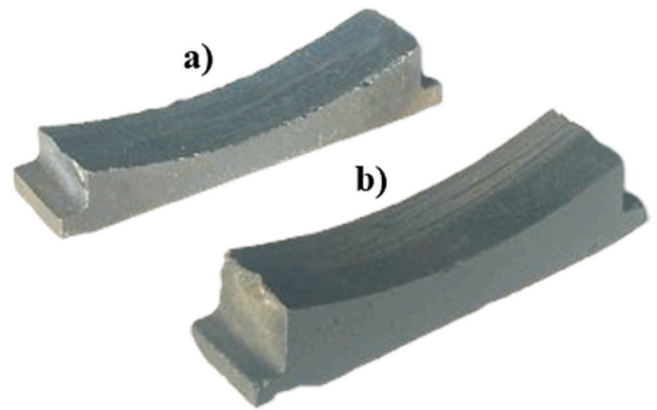


Fig. 4. Scaled brake shoe specimens. (a) Is made of cast iron and (b) is made of K-type composite material.

freight-wagon keepers and is approved by the UIC and listed in Appendix M of the UIC 541-4 leaflet [4]. The K-type shoe is a non-asbestos friction material containing metal, compounded with a special resin. The main properties of the shoe are listed in Table 3.

Before testing, the wheel tread was cleaned, and a bedding-in procedure was carried out for each shoe to ensure conformity with the wheel profile and to stabilize contact conditions. The bedding-in procedure was carried out according to a strategy similar to the approach described in the EN 16452 standard [5], i.e., through repeated drag braking operations with intermediate cooling until observing that at least 80% of the friction material surface had proper contact. Throughout both bedding-in and testing operations, to account for the heat generated by friction, cooling fans mounted on the side of the test bench operated constantly to prevent excessive heating of the components, as high temperatures may significantly alter material properties. During tests, the cooling fans were powered to avoid the contacting

Table 2
Overview of the parameters for drag braking tests.

Duration of the test (s)				
Speed a	Pressure			
	0.3 MPa	0.6 MPa	0.8 MPa	1.2 MPa
30 km/h	100	50	38	25
50 km/h	60	30	23	15
70 km/h	43	22	18	11
90 km/h	34	17	13	9

Table 3
Main properties of the K-type shoe considered in this test.

Property	Value
Density	2000 kg/m ³
Hardness (HRR)	110
Thermal conductivity	0.8 W/(m·K)
Specific thermal capacity	1000 J/(kg·K)
Module of compression elasticity (@ 20 °C)	1900 MPa
Compressive strength	105 MPa

bodies to heat up to temperatures potentially leading to a big variation of the main material properties. Furthermore, to avoid excessive heat, the duration of each drag braking tests was set to approximately keep a constant value of the product of time, pressure and speed, meaning that tests with higher values of speed and pressure lasted significantly less than those at low speed and pressure, see Table 2. In this way the impact of temperature on global tribological quantities obtained during the experimental campaign, namely average friction coefficient and wear, is minimised. The effectiveness of these precautions was also assessed by measuring the temperature of the brake shoe using a thermocouple after each test.

It is important to note that, although Pascal's similitude model implies unitary scaling of contact pressure and sliding speed (see Table 1), it does not entail a linear scaling of thermal phenomena, since like all scaling rules, it does not ensure perfect scaling of all physical quantities. Nonetheless, it is believed that Pascal's rule is suited for the goal of the present paper, which is to perform a relative comparison of the global wear rate of the two tested shoe materials. Additionally, by carefully controlling the operating conditions, i.e., performing drag-braking tests under steady-state conditions and limiting excessive temperature rises thanks to the cooling fans, it is possible to obtain a meaningful macroscopic comparison between cast iron and composite brake shoes.

2.3. Experimental data processing

For each selected speed-pressure combination, the shoe was mounted on the brake holder, to ensure proper alignment with the wheel tread. Using a dedicated LabVIEW programme, the rail-disc motor, that in turns drives the wheel-disc, was controlled to spin at constant speed. Once the desired rotational speed was achieved, the cylinder was actuated to press the shoe against the tread for the specified duration. To improve test repeatability, each test was followed by a cooling period to allow both the wheel and brake shoe temperature to decrease and get back to room temperature, while keeping the fans activated.

The test bench is equipped with multiple transducers: two encoders measure the rotational speed of each shaft, a torque meter records the torque on the rail shaft, and the applied braking pressure is monitored directly through a voltage signal provided by the proportional valve. During each test, the torque on the rail shaft was measured using the torque meter, the rotational speed of each roller was recorded by the encoders, and air supply pressure was obtained from the proportional valve as a voltage signal, which is related to the braking force using the previously identified calibration. From these parameters, it is possible to estimate in each time instant the value of the wheel-shoe friction coefficient as well as the energy dissipated during the drag braking test. The COF μ is obtained as:

$$\mu = \frac{C_w}{F_N \cdot R_w} = \frac{C_r - C_{r0}}{\tau_{nom} \cdot F_N \cdot R_w} \quad (1)$$

where the subscripts w and r refer to the wheel and rail respectively, C is the torque on the corresponding shaft, the subscript 0 refers to the idle torque when no braking effort is applied, F_N is the wheel-shoe normal force, τ_{nom} is the nominal transmission ratio and R is the given roller radius. The nominal transmission ratio is defined as:

$$\tau_{nom} = \frac{\omega_w}{\omega_r} \quad (2)$$

where ω is the rotational speed of the shaft. The nominal transmission ratio was determined to be 1.4 during the initial calibration of the bench.

Each pressure-speed configuration was investigated with sets of experimental tests including repetitions with intermediate cooling to increase the total amount of worn material and dissipated energy, while avoiding overheating. After each repetition, the shoe and wheel were allowed to cool down before repeating the same configuration. Cast iron shoe tests were repeated twice, while composite shoe tests were

repeated six times, as the material has a lower wear rate and requires higher energy dissipation for measurable worn mass. After each set of tests run for one combination of speed and pressure, the amount of cumulated worn material was evaluated in terms of mass loss by weighing the brake shoe specimen with a high-resolution scale (KERN ALJ 220-4NM). Weighing of the specimen was performed at the beginning and end of each set only, to increase the robustness of the collected data. As the experimental campaign led to significant wear of the tested shoes, and due to the long times of the activity, it was not possible to repeat the same set multiple times. Therefore, weighing specimens only at the end of each test was done specifically to smooth over possible fluctuations of the wear rate and collect more robust data, which is believed to correspond steady-state wear rates. The main technical specifications of the high-resolution scale are given in Table 4.

The material loss was related to the amount of dissipated energy, coherently with existing literature works [23,38]. The energy dissipated during a single test E is evaluated as the following integral, which is calculated numerically with a dedicated MATLAB script for experimental data post-processing:

$$E_i = \int_{t_{in,i}}^{t_{end,i}} P_{diss} dt = \int_{t_{in,i}}^{t_{end,i}} (C_r - C_{r0}) \cdot \omega_r dt \quad (3)$$

where subscript i refers to the i -th test, t_{in} and t_{end} are the initial and final times of the test respectively, P_{diss} is the dissipated power. This equation assumes perfect adhesion between the two rollers, as slip is negligible due to high normal load applied by the compression springs. The negligible slip condition was also verified by using the velocity data gathered from the encoders of the two discs, which display a constant transmission ratio between the two discs throughout the whole test, with no significant changes observed when applying the braking torque on the wheel disc.

Finally, the wear rate for each set of drag braking tests was obtained as the ratio between the mass lost due to wear and the energy dissipated due to friction:

$$W_{m-i} = \frac{m_{worn-i}}{E_i} \quad (4)$$

where subscript i refers again to the i -th test, W_m is the wear rate expressed as a function of mass, m_{worn} is the worn mass and E is the energy dissipated. It should be emphasized that, with Pascal's rule, the scaling factor for wear rate is equal to the ratio of the scaling factors for mass and energy, which is nominally unitary, see Table 1. This means that the global wear rate factor for experimental tests run with the scaled twin-disc test rig can be considered to be in the same order of magnitude as that of the full-scale system. This is a great benefit of adopting Pascal's scaling rule, which is particularly suitable for investigating tribological phenomena.

The results of the experimental campaign were adopted to build a simplified analytical model for the estimation of the worn mass for both tested shoe materials, assuming drag braking operation and steady-state conditions. The analytical model considers a relationship between worn mass and dissipated energy, with a proportionality coefficient that varies with speed and average contact pressure, as stated by the following expression:

Table 4
Main data of the high-resolution scale (KERN ALJ 220-4NM).

Specification	Value
Max Capacity	220 g
Readability	0.1 mg
Minimum weight	10 mg
Calibration class	I
Repeatability	0.2 mg
Linearity	±0.2 mg
Stabilization time (typical)	4 s

$$m_{\text{worn}} = k_{\text{wear}}(V, p_{\text{ws}}) \cdot E \quad (5)$$

where V is speed, p_{ws} is the average wheel-shoe contact pressure and k_{wear} is the proportionality coefficient. The dependency of the wear coefficient on speed and contact pressure was modelled as a power equation tuned on the collected experimental data.

3. Results and discussion

The data gathered from the tests was used to perform two comparative studies: an analysis on the wear rates of the two materials and the evaluation of the coefficient of friction between shoe and wheel.

The resulting wear rates, for both the cast iron and composite blocks, are reported in [Tables 5 and 6](#) respectively. The wear rate value is much higher in the P10 block, indicating that the composite material has greater wear resistance. In addition, the two materials have opposite behaviours with respect to speed, as for the composite the wear rate increases with increasing speed, while the opposite is true for the cast iron block.

The experimental data was fitted using a power equation, which allows to obtain the wear rate as a function of pressure and velocity. The power equation is:

$$k_{\text{wear}}(V, p_{\text{ws}}) = a \cdot p_{\text{ws}}^b \cdot V^c \quad (6)$$

where k_{wear} is the wear rate in mg/kJ, p_{ws} is the pressure in MPa, V is speed in km/h, and a , b and c are the model parameters, which depend on the material that is being considered. The term a can be interpreted as a base wear rate, which is related to the tested materials and contact conditions. On the other hand, the exponents b and c are related to the sensitivity of the wear rate on contact pressure and speed, respectively. Exponent values close to 1 suggest a linear dependency, while values close to 0 mean that the corresponding parameter does not affect the wear coefficient. If both exponents were close to 0, the worn mass would be directly proportional to the amount of dissipated energy.

The model coefficients for P10 cast iron and composite shoes were identified from tuning of the experimental data with a MATLAB routine, implementing a linear ordinary least-squares (OLS) regression after the application of a logarithmic transformation that allows to obtain the linear model:

$$\log k_{\text{wear}}(V, p_{\text{ws}}) = \log a + b \log p_{\text{ws}} + c \log V \quad (7)$$

The linear model obtained with logarithmic transformation allows to define a convex loss function that features a global minimum. This ensures that a unique vector of optimal model coefficients can be found at a small computational cost. For each shoe material, the model coefficients are identified considering all 16 experimental records. To statistically assess the performances of the fitting model, a leave-one-out cross-validation (LOOCV) was implemented, hence obtaining 16 sets of the model coefficients with one experimental record left out from the regression training set. This allows to estimate the average values of the model coefficients as well as the 95%-confidence interval (CI) bounds. Additionally, the model performance was assessed in terms of the R^2 score on the results of the LOOCV, which is calculated as:

Table 5
Wear rates for cast iron shoes.

Mass wear rates for cast iron (mg/kJ)				
Speed a	Pressure			
	0.3 MPa	0.6 MPa	0.8 MPa	1.2 MPa
30 km/h	3.55	5.81	6.44	13
50 km/h	2.11	2.24	5.16	8
70 km/h	1.90	2.59	3.42	6.22
90 km/h	2.65	3.04	3.58	7.37

Table 6
Wear rates for K-type composite shoes.

Mass wear rates for composite (mg/kJ)				
Speed a	Pressure			
	0.3 MPa	0.6 MPa	0.8 MPa	1.2 MPa
30 km/h	0.053	0.071	0.082	0.146
50 km/h	0.092	0.096	0.126	0.186
70 km/h	0.116	0.153	0.180	0.200
90 km/h	0.158	0.216	0.259	0.338

$$R_{\text{LOO}}^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i^{(-i)})^2}{\sum_i (y_i - \bar{y})^2} \quad (8)$$

where y is the dependent variable, namely the wear rate in the context of the present paper, i is the summation counter, $\bar{y}$ is the mean value of the observed samples and $\hat{y}_i^{(-i)}$ is the prediction for the i -th sample obtained when that sample is left out during the identification of the model coefficients.

[Table 7](#) provides the values of the model coefficients identified through OLS together with the mean values, 95%-confidence interval bounds and R^2 score estimated via LOOCV. [Figs. 5 and 6](#) depict the experimental data points as circles grouped by velocity, and the power equation fitting model as a surface, showing that there is an acceptable agreement between the experimental records and the model. From [Tables 7](#) and it can be inferred that the fitting model for the composite material features better prediction capabilities with respect to the regression obtained for the cast iron shoe. This behaviour can be justified by the fact that the composite material tends to have a more stable friction coefficient and hence tribological properties when compared to traditional P10 cast iron shoes. Furthermore, a detailed data analysis highlighted that the regression model for cast iron shoes struggles with the predictions for values of contact pressure and running speed close to the bounds of the tested experimental map.

The composite material exhibits a positive c coefficient, while for the cast iron c is negative, suggesting that the two materials have opposite wear behaviour with speed. This could be related to differences in the dominating wear mechanisms for the two materials, which however will require further studies for confirmation and clarification. Concerning cast iron, the wear rate tends to decrease with speed, and this could be due to the generation of a layer of oxide and/or metal debris which

Table 7
Power law fit parameters, for cast iron and composite.

	Cast iron		Composite	
a (mg/kJ)	Value	51.072	Value	4.375e-3
	Mean	51.954	Mean	4.390e-3
	95% CI Upper Bound	57.665	95% CI Upper Bound	4.635e-3
	95% CI Lower Bound	46.244	95% CI Lower Bound	4.146e-3
b	Value	0.8431	Value	0.5277
	Mean	0.8438	Mean	0.5274
	95% CI Upper Bound	0.8659	95% CI Upper Bound	0.5387
	95% CI Lower Bound	0.8218	95% CI Lower Bound	0.5160
c	Value	-0.5336	Value	0.9180
	Mean	-0.5335	Mean	0.9185
	95% CI Upper Bound	-0.5081	95% CI Upper Bound	0.9333
	95% CI Lower Bound	-0.5589	95% CI Lower Bound	0.9038
R_{LOO}²		72.56%		88.45%

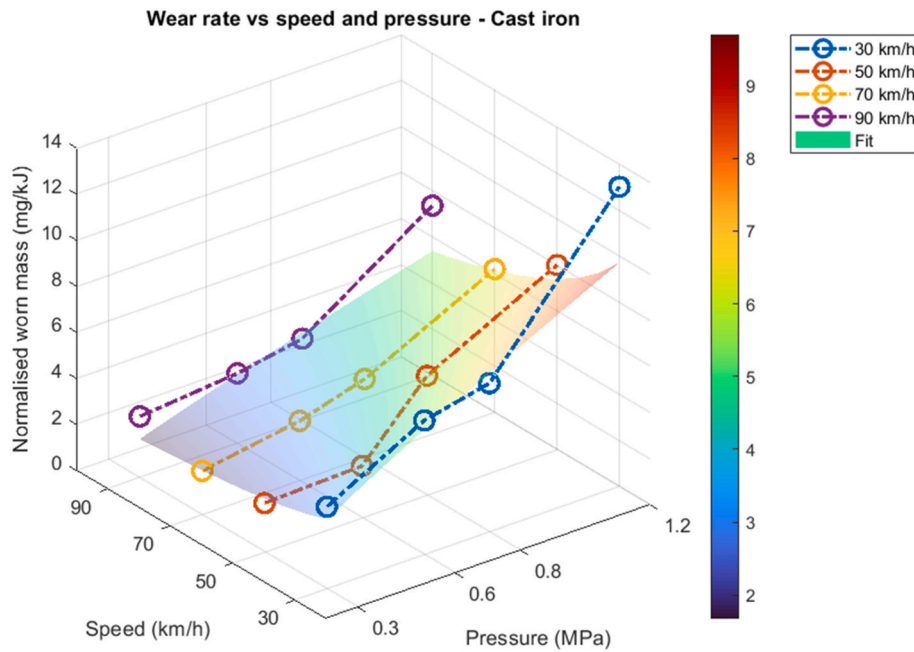


Fig. 5. Experimental data and fit power law, for cast iron.

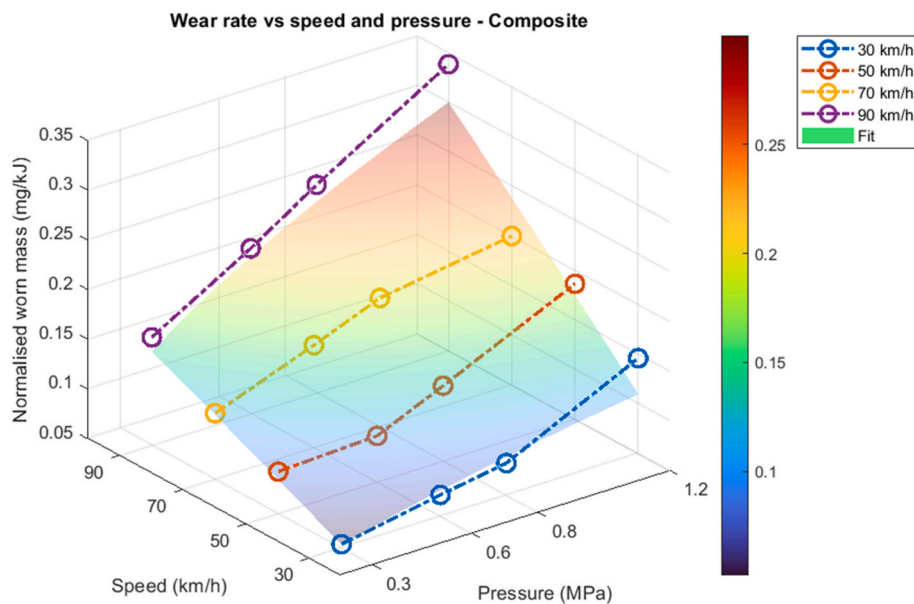


Fig. 6. Experimental data and fit power law, for composite.

becomes more stable at higher speeds, hence acting as a lubricant preventing from direct metal-to-metal contact and hence leading to smaller amounts of worn materials. On the other hand, the composite shoe features an increasing wear rate with speed, and this could be due to a degradation of the composite matrix at higher temperatures. Furthermore, since composite shoes are known to have far lower thermal conductivity than cast iron, local flash temperatures could become higher at higher speed, hence triggering thermal delamination and abrasive wear, eventually increasing the amount of worn material. Please note that these considerations are just preliminary hypotheses, that will require deeper analysis for justification or for the identification of other possible explanations to the observed behaviour. The mechanistic interpretation of the observed behaviour is demanded to future works and will be performed mainly through surface analysis. The latter was not carried out in the activities described in the paper due to reasons related to costs

and duration of the experimental campaign.

To further prove the robustness and validity of the adopted regression models, Fig. 7 reports a residual diagnostic based on the LOOCV predictions. Residuals are calculated in the logarithmic space to ensure consistency with the formulation reported in Equation (7). The residual plot for the cast iron shoe, see Fig. 7a), is distributed around the zero line without noticeable systematic trends. Some dispersion can be noticed and is confirmed by the residual distribution in Fig. 7b), which however remains unimodal and zero-centred. For the composite shoe, see the residual plot in Fig. 7c) and the residual distribution in Fig. 7d), the residuals have a more compact and stable distribution, hence not suggesting dominant systematic trends or evident bias. Overall, the residual analysis confirms that no significant systematic bias or influential outlier is affecting the models for either materials.

It is important to remark that the derived fitting models should be

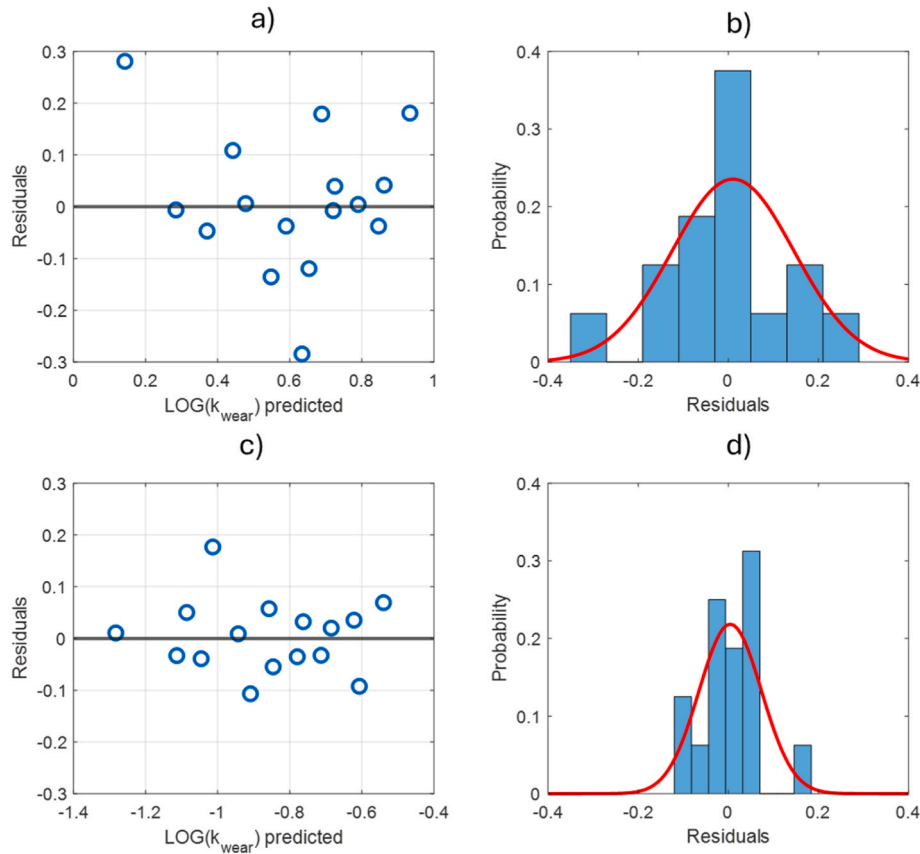


Fig. 7. Residual diagnostics of the regression wear model based on leave-one-out cross-validation predictions. (a) Residuals versus LOOCV predicted logarithmic wear rate for cast iron shoes; (b) histogram of cast iron residuals evaluated in log10 scale. (c) Residuals versus LOOCV predicted logarithmic wear rate for composite shoes; (d) histogram of composite residuals evaluated in log10 scale.

employed only within the tested range of contact pressure and speed values, as due to the strong nonlinearities characterizing tribological phenomena, the extrapolation of the models could bring to unreliable predictions. Nonetheless, the tested experimental map covers most of the common values of speed and pressure for braking of freight wagons. Additionally, it should be noted that the wear coefficients were determined under drag braking tests, hence under stable operating conditions. The extension of the fitting models to stop braking operations, where transient effects dominate with changes of speed and pressure, could be misleading. Future upgrades of the activity will deal with the assessment of wear under stop braking operations and with possible correction of the fitting models. Nevertheless, the fitting models can still be adopted for a preliminary comparison of the expected life of the two types of tested shoe materials. In addition, the wear model derived in this work is valid only in a temperature range in which globally the material properties, especially the Young's modulus, are not expected to change significantly. This assumption was verified by measuring the shoe temperature with a contact thermocouple at the end of each test, in order to assess the effectiveness of the fan cooling. Measurements were taken at a location as close as possible to the wheel-shoe contact surface. The maximum temperatures recorded are 108 °C for the P10 shoe and 145 °C for the K-type composite shoe, while the average values measured for each set of tests range between 40 and 90 °C for cast iron and 40–95 °C for K-type composites. These values are not intended to provide a detailed description of the thermal behaviour of the materials, but rather to give an indication about the average temperature rise in the shoe. In fact, the recorded temperatures only provide an average description of the temperature field inside the shoe, but local flash temperatures during the application of the braking torque are expected to be much higher. Therefore, the results of the experimental activity

cannot be extended to local wear analyses. Future upgrades of the test rig will allow to continuously monitor the temperature during testing, so that a correlation between temperature and wear may be identified.

Due to the difference in density between cast iron and type-K composites, comparing the volume wear rate is more appropriate and allows for a direct comparison of the wear depth, which ultimately determines the operating life of the brake shoes. The volume wear rates were obtained simply by dividing the mass wear rate by the corresponding density. A density of $\rho_{P10} = 7100 \text{ kg/m}^3$ was used for phosphorus cast iron with chemical composition as complying with the UIC 832 standard [39] while for the K-type composite shoe, the manufacturer specified a density of $\rho_K = 2000 \text{ kg/m}^3$. The values of worn volume rate calculated for the two materials are plotted in Fig. 8.

Table 8 contains the ratios of volume wear rate for cast iron over composite, which allow to directly compare the two behaviours. Cast iron presents much higher volume wear rates than the K-type composite,

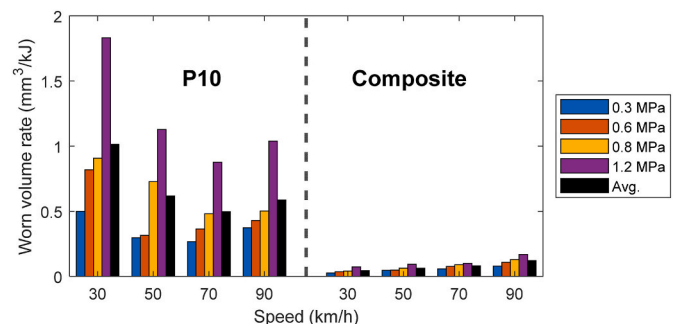


Fig. 8. Volume wear rates for the two materials.

Table 8

Volume wear rates ratios, between volume wear rates of P10 and K-type composite shoes.

Volume wear rate ratios				
Speed a	Pressure			
	0.3 MPa	0.6 MPa	0.8 MPa	1.2 MPa
30 km/h	18.70	22.94	22.05	25.15
50 km/h	6.44	6.53	11.58	12.12
70 km/h	4.59	4.75	5.36	8.77
90 km/h	4.71	3.97	3.88	6.14

with ratios ranging between 4 and 25 times, increasing with pressure and decreasing with speed. The average wear rate ratio between the two materials is approximately equal to 10.5, suggesting that composite shoes could have a lifespan ten times longer than their cast iron counterparts, this result is consistent with what was found by Walia et al. [25]. Please note that although this estimate accounts only for the global wear of the brake shoe and does not include local damage mechanisms, it still provides relevant information for brake shoe manufacturers and freight wagon keepers, as it directly relates to expected replacement intervals and overall performance of the shoe.

Regarding the COF, its mean value was evaluated using Equation (1). Table 9 shows the COF for cast iron, while Table 10 shows its value for the composite. The COF of cast iron decreases with increasing speed and pressure, as described in Karwatzki's equation [40] which is commonly used in longitudinal train dynamics (LTD) simulations. Contrarily, while the K-type composite sees a decrease in COF due to increasing speed, pressure has close to zero effect. At low pressures, the COF of the P10 and composite shoes are comparable, while at higher pressure levels difference between the two becomes much more significant. The K-type composite has a tighter range of COF values, as expected, while the cast iron has a much higher variability.

The COF was analysed in terms of mean values to fairly compare the cast iron and composite shoes, disregarding the transient phase and the fluctuations. Figs. 9 and 10 show the trend of the friction coefficient during a test at 50 km/h with a pressure of 0.6 MPa, for both cast iron and composite. It can be seen that the transient phase lasts only for some fractions of a second, with a peak corresponding to the onset of contact between the shoe and the wheel, and then the COF oscillates around a stable mean value. The general transient and steady-state is the same for other tests, with different pressure and speed parameters.

4. Conclusions

This study comprehensively maps the tribological behaviour of a traditional cast iron and a new K-type composite shoe under braking at constant speed as a function of speed and contact pressure. Experimental tests were carried out on a scaled twin-disc rig following Pascal's similitude rule, that ensures a unitary scaling of the wear rate, i.e., the ratio between the worn mass/volume over dissipated energy. The main findings of the activity are given in the bulleted list below:

- The traditional cast iron brake shoe has a much higher wear rate with respect to the K-type composite material. In terms of worn volume,

Table 9

COF for cast iron shoes.

COF (–)				
Speed a	Pressure			
	0.3 MPa	0.6 MPa	0.8 MPa	1.2 MPa
30 km/h	0.38	0.31	0.28	0.24
50 km/h	0.32	0.25	0.22	0.17
70 km/h	0.28	0.22	0.22	0.17
90 km/h	0.24	0.22	0.18	0.16

Table 10

COF for K-type composite shoes.

COF (–)				
Speed a	Pressure			
	0.3 MPa	0.6 MPa	0.8 MPa	1.2 MPa
30 km/h	0.35	0.37	0.33	0.30
50 km/h	0.26	0.31	0.29	0.29
70 km/h	0.28	0.24	0.25	0.27
90 km/h	0.26	0.27	0.25	0.23

the wear rate of the cast iron shoe is observed to be around 10.5 times higher. This means that, at least when considering macroscopic phenomena, the new composite shoes can have a longer operating life, thus reducing the number of shoe replacements, with substantial cost savings. Nonetheless, future activities should investigate the behaviour of the wheel as well, as due to their lower thermal conductivity, composite shoes lead to higher thermal stresses in the wheel steel. Furthermore, future developments shall deal with the investigation of local damage phenomena that could impact the behaviour of the materials, also changing the ratio between the wear rates.

- The cast iron and composite shoes exhibit an opposite trend of the wear rate with speed. Wear of the cast iron tends to decrease at higher speeds, while the K-type composite shoe features an increasing wear with speed. On the other hand, for both materials, the wear rate is higher at higher values of the wheel-shoe contact pressure.
- For both tested materials, a simple analytical law is derived by fitting the experimental data. The analytical law allows to calculate the amount of worn material as a function of contact pressure and speed. The derived equations feature good prediction capabilities, as proved through LOOCV, with no significant bias or systematic trend. In future upgrades, these laws could be used for a preliminary estimation of the evolution of wear of the brake shoes under real drag braking operating conditions. On the other hand, the extension to stop braking operations requires additional tests, since in stop braking operations, transient phenomena dominate over steady-state ones.
- The COF of the cast iron shoe material increases with decreasing contact pressure and speed, and this is in good agreement with Karwatzki's law. On the other hand, the K-type composite material exhibits a negligible dependency on contact pressure. Overall, the K-type composite spans a tighter range of COF values, thus exhibiting greater stability, while the cast iron features a wider variation.

It is worth pointing out that the results of the present study were obtained under braking operations at constant speed with fans continuously cooling down the system, to avoid reaching high temperatures and to experimentally determine wear rates under stable speed and pressure conditions. Therefore, the applicability of the model is limited to drag braking operations, in the speed and pressure ranges examined in the present work. Using the model to extrapolate data beyond these ranges, especially regarding pressure, would exceed common freight-train braking conditions, leading to unrealistic results. In future upgrades, the comparison shall be extended to stop braking operations and to the investigation of the thermal behaviour of the wheel and brake shoe when different shoe materials are adopted. Furthermore, as several K-type composite shoe materials are homologated, future investigations should deal with testing of these additional materials, to understand whether there is consistency in their behaviour, or if variations are present among this type of shoes. In addition, future activities should focus on characterizing the emissions generated by cast iron and composite materials. In fact, although cast iron tends to exhibit higher material loss, it will be equally important to analyze the spectrum of the particle size for the emitted debris, which is receiving growing concerns

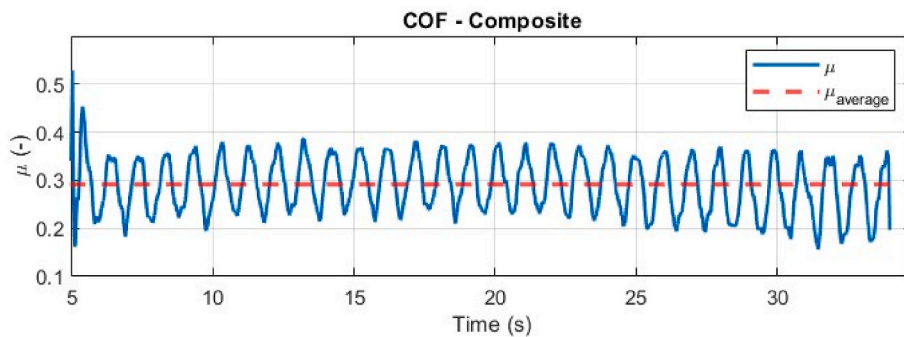


Fig. 9. Cast iron COF trend with respect to time, test at 50km/h and 0.6MPa

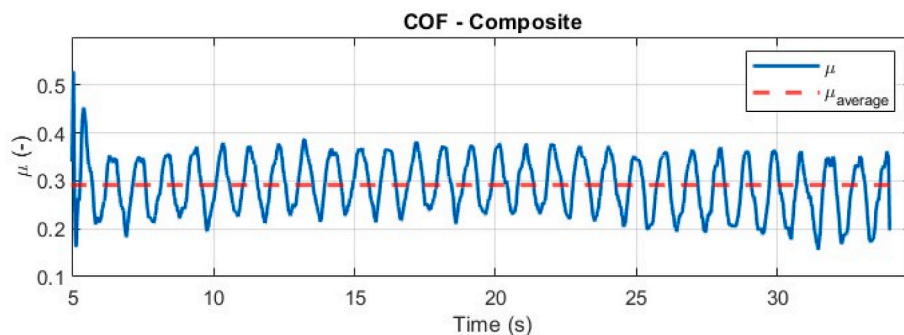


Fig. 10. Composite COF trend with respect to time, test at 50 km/h and 0.6 MPa.

due to the impact on human health. Investigations regarding the wear effect on microstructure and surface aspect may also be carried out as well as debris and particle analysis, in order to define the dominant wear mechanisms and relate them to global wear, observed on a larger scale.

Moreover, future developments shall deal reproducing real dynamic operations on the scaled rig, so that it could be possible to validate the recorded wear against the prediction of the derived analytical models. This will also thrust the implementation of the analytical wear models within dynamic simulation codes, thus allowing to estimate the amount of worn material under specific trips and train operations.

CRediT authorship contribution statement

M. Magelli: Conceptualization, Investigation, Methodology, Software, Supervision, Writing – review & editing. **R. Pagano:** Data curation, Investigation, Software, Visualization, Writing – original draft. **A. Stagni:** Data curation, Formal analysis, Validation, Visualization, Writing – original draft. **N. Zampieri:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nicolo' Zampieri reports financial support was provided by Government of Italy Ministry of University and Research (MUR), grant number FISA-2023-00314. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

References

- [1] U. Olofsson, A study of airborne wear particles generated from the train traffic—Block braking simulation in a pin-on-disc machine, *Wear* 271 (1) (2011) 86–91, <https://doi.org/10.1016/j.wear.2010.10.016>.
- [2] Y. Lyu, E. Bergseth, M. Tu, U. Olofsson, Effect of humidity on the tribological behaviour and airborne particle emissions of railway brake block materials, *Tribol. Int.* 118 (2018) 360–367, <https://doi.org/10.1016/j.triboint.2017.10.011>.
- [3] R. Ozaki, K. Handa, S. Saga, K. Ikeuchi, Comparison of the particle emission characteristics of cast iron, organic composite, and sintered composite brake blocks for railway tread brakes, *Wear* 578–579 (2025) 206170, <https://doi.org/10.1016/j.wear.2025.206170>.
- [4] UIC 541-4, Brakes – Brakes with Composite Brake Blocks – General Conditions for the Certification of Composite Brake Blocks, 2010.
- [5] EN 16452:2015. Railway Applications - Braking - Brake Blocks.
- [6] L. Cantone, A. Ottati, Modelling of friction coefficient for shoes type LL by means of polynomial fitting, *Open Transport. J.* 12 (1) (2018).
- [7] L. Ghidini, A. Mazzù, M. Faccoli, Experimental study of wear and rolling contact fatigue in railway wheel steels coupled with various brake block materials: insights from innovative small-scale testing, *Wear* (2024) 558–559, <https://doi.org/10.1016/j.wear.2024.205558>.
- [8] G. Megna, A. Bracciali, Tread-braked wheels: review and recent findings, *Machines* 13 (7) (2025) 579, <https://doi.org/10.3390/machines13070579>.
- [9] A. Somà, M. Aimar, N. Zampieri, Simulation of the thermal behavior of cast iron brake block during braking maneuvers, *Appl. Sci.* 11 (11) (2021), <https://doi.org/10.3390/app11115010>.
- [10] P. Monreal-Perez, D. Elduque, D. López, I. Sola, J. Yaben, I. Clavería, Full-scale dynamometer tests of composite railway brake shoes including latex sheep wool fibers, *J. Clean. Prod.* 379 (2022), <https://doi.org/10.1016/j.jclepro.2022.134533>.
- [11] I. Bodini, C. Petrogalli, M. Faccoli, A. Mazzù, Vision-based damage analysis in shoe-braking tests on railway wheel steels, *Wear* (2022) 510–511, <https://doi.org/10.1016/j.wear.2022.204514>.
- [12] C. Felhö, G. Hegedüs, L. Kuzsella, K. Voith, D. Drees, Experimental investigations of the wear behaviour of railway brake block raw materials, *J. Phys. Conf.* 2848 (1) (2024), <https://doi.org/10.1088/1742-6596/2848/1/012004>.
- [13] T. Vernersson, R. Lundén, S. Abbasi, U. Olofsson, Wear of railway brake block materials at elevated temperatures: pin-on-disc experiments, in: *Presented At: Eurobrake, 2012. Dresden (Germany)*.
- [14] M. Faccoli, N. Zani, A. Ghidini, C. Petrogalli, Experimental and numerical investigation on the wear behavior of high performance railway wheel steels paired with various brake block materials under dry sliding conditions, *Wear* (2022) 506–507, <https://doi.org/10.1016/j.wear.2022.204456>.
- [15] N. Bosso, N. Zampieri, Numerical stability of co-simulation approaches to evaluate wheel profile evolution due to wear, *Int. J. Real. Ther.* 8 (2) (2020) 159–179, <https://doi.org/10.1080/23248378.2019.1672588>.

- [16] P.A. de Paula Pacheco, M. Magelli, M.V. Lopes, P.H.A. Correa, N. Zampieri, N. Bosso, et al., The effectiveness of different wear indicators in quantifying wear on railway wheels of freight wagons, *Railway Engineering Science* 32 (3) (2024) 307–323, <https://doi.org/10.1007/s40534-024-00334-8>.
- [17] J.F. Archard, Contact and rubbing of flat surfaces, *J. Appl. Phys.* 24 (8) (1953) 981–988.
- [18] J.F. Archard, W. Hirst, The wear of metals under unlubricated conditions, *Proceedings of the Royal Society of London A Mathematical and Physical Sciences* 236 (1206) (1956) 397–410, <https://doi.org/10.1098/rspa.1956.0144>.
- [19] T. Jendel, Prediction of wheel profile wear—comparisons with field measurements, *Wear* 253 (1) (2002) 89–99, [https://doi.org/10.1016/S0043-1648\(02\)00087-X](https://doi.org/10.1016/S0043-1648(02)00087-X).
- [20] T.G. Pearce, N.D. Sherratt, Prediction of wheel profile wear, *Wear* 144 (1) (1991) 343–351, [https://doi.org/10.1016/0043-1648\(91\)90025-P](https://doi.org/10.1016/0043-1648(91)90025-P).
- [21] R. Lewis, F. Braghni, A. Ward, S. Bruni, R.S. Dwyer-Joyce, K. Bel Knani, et al., Integrating dynamics and wear modelling to predict railway wheel profile evolution, in: A. Ekberg, E. Kabo, J. Ringsberg (Eds.), 6th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems : CM2003, CHARMEC, Gothenburg (Sweden), 2003.
- [22] J. Pombo, J. Ambrósio, M. Pereira, R. Lewis, R. Dwyer-Joyce, C. Ariauo, et al., Development of a wear prediction tool for steel railway wheels using three alternative wear functions, *Wear* 271 (1) (2011) 238–245, <https://doi.org/10.1016/j.wear.2010.10.072>.
- [23] R. Enblom, M. Berg, Simulation of railway wheel profile development due to wear—influence of disc braking and contact environment, *Wear* 258 (7) (2005) 1055–1063, <https://doi.org/10.1016/j.wear.2004.03.055>.
- [24] K. Ikeuchi, K. Handa, R. Lundén, T. Vernersson, Wheel tread profile evolution for combined block braking and wheel–rail contact: results from dynamometer experiments, *Wear* 366–367 (2016) 310–315, <https://doi.org/10.1016/j.wear.2016.07.004>.
- [25] M.S. Walia, T. Vernersson, R. Lundén, F. Blennow, M. Meinel, Temperatures and wear at railway tread braking: field experiments and simulations, *Wear* (2019) 440–441, <https://doi.org/10.1016/j.wear.2019.203086>.
- [26] P. Wang, X. Yang, G. Tao, Z. Wen, Development of a wheel wear prediction model considering the interaction of abrasive block–wheel and wheel–rail, *Wear* 550–551 (2024) 205418, <https://doi.org/10.1016/j.wear.2024.205418>.
- [27] M.R.K. Vakkalagadda, D.K. Srivastava, A. Mishra, V. Racherla, Performance analyses of brake blocks used by Indian Railways, *Wear* 328–329 (2015) 64–76, <https://doi.org/10.1016/j.wear.2015.01.044>.
- [28] W.J. Wang, F. Wang, K.K. Gu, H.H. Ding, H.Y. Wang, J. Guo, et al., Investigation on braking tribological properties of metro brake shoe materials, *Wear* 330–331 (2015) 498–506, <https://doi.org/10.1016/j.wear.2015.01.057>.
- [29] A.K. Ilanko, S. Vijayaraghavan, Wear behavior of asbestos-free eco-friendly composites for automobile brake materials, *Friction* 4 (2) (2016) 144–152, <https://doi.org/10.1007/s40544-016-0111-0>.
- [30] Y. Lyu, Q. Zhang, L. Tanzeglock, M. Tu, J. Mo, T. Okuda, et al., Mapping of friction, wear and particle emissions from high-speed train brakes, *Wear* 572–573 (2025) 206027, <https://doi.org/10.1016/j.wear.2025.206027>.
- [31] V. Francesco, C. Davide, L. Yezhe, W. Jens, Simulation of friction and wear for a low-steel brake material based on experimental pv-mapping of its basic constituents, *Wear* 572–573 (2025) 206037, <https://doi.org/10.1016/j.wear.2025.206037>.
- [32] A. Jaschinski, H. Chollet, S. Iwnicki, A. Wickens, J. Würzen, The application of roller rigs to railway vehicle dynamics, *Veh. Syst. Dyn.* 31 (5–6) (1999) 345–392, <https://doi.org/10.1076/vesd.31.5.345.8360>.
- [33] N. Bosso, P. Allen, N. Zampieri, Scale testing theory and approaches, in: S. Iwnicki, M. Spiriyagin, C. Cole, T. McSweeney (Eds.), *Handbook of Railway Vehicle Dynamics*, CRC Press, Boca Raton (FL, USA), 2019, pp. 825–867.
- [34] M. Magelli, R. Pagano, N. Zampieri, Design of an innovative twin-disc device for the evaluation of wheel and rail profile wear, *Design* 8 (4) (2024), <https://doi.org/10.3390/designs8040073>.
- [35] M. Magelli, R. Pagano, N. Zampieri, Adapting a scaled twin-disc device for tread braking investigations based on an ad-hoc thermal similitude model, *Wear* 574–575 (2025) 206105, <https://doi.org/10.1016/j.wear.2025.206105>.
- [36] N. Bosso, M. Magelli, N. Zampieri, Long train dynamic simulation by means of a new in-house code, in: G. Passerini, J.M. Mera, R. Takagi (Eds.), *WIT Transactions on the Built Environment* 199, WIT Press, Southampton (UK), 2020, pp. 249–259, <https://doi.org/10.2495/CR200231>.
- [37] N. Bosso, M. Magelli, N. Zampieri, A numerical method for the simulation of freight train emergency braking operations based on the UIC braked weight percentage, *Railway Engineering Science* (2023), <https://doi.org/10.1007/s40534-022-00296-9>.
- [38] B. Peng, S. Iwnicki, P. Shackleton, D. Crosbee, Comparison of wear models for simulation of railway wheel polygonization, *Wear* 436–437 (2019) 203010, <https://doi.org/10.1016/j.wear.2019.203010>.
- [39] UIC 832, Technical Specification for the Supply of brake-shoes Made from Phosphoric Iron for Tractive and Trailing Stock, 2015.
- [40] L. Cantone, L. Müller, D. Negretti, V. Vullo, TrainDy, A new UIC simulator for the longitudinal dynamics of trains, in: *WIT Transactions on the Built Environment*, vol 103, WIT Press, Southampton (UK), 2008, pp. 735–744, <https://doi.org/10.2495/CR080711>.