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Analysis of Abnormal Wear Patterns of Pantograph Strip in Urban Rail Systems Based on Long-Term Maintenance Data

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Abstract

Abnormal wear of pantograph strips is a key reliability problem in urban rail systems using rigid catenary power supply. This short paper summarizes a data-driven and experimental study based on long-term maintenance data from Tianjin Metro Line 6, microscopic observations, correlation analysis, and ring-on-block tests. The results show a three-stage wear evolution process: normal wear, mild abnormal wear, and severe abnormal wear. Low relative humidity, especially below 35%, and insufficient contact force trigger mild arcing, carbon-film depletion, surface roughening, material transfer, and finally severe arc ablation. The findings provide a concise mechanism and maintenance guidance for metro pantograph-catenary interfaces.

Keywords: pantograph, overhead conductor rail, pantograph--overhead contact line, railway overhead line, carbon strip, scrap, wear, graphite, recycle, surface coating, wear.

1 Introduction

Rigid catenary systems are widely used in underground metro lines because of their compact layout and high reliability [1], as shown in Fig. 1. The pantograph strip and contact wire form a continuous sliding electrical contact, so interface stability directly affects current collection quality, strip service life, and maintenance cost. Normal strip degradation is usually a gradual tribological process governed by contact force, current, temperature, humidity, and material properties [2]-[4].

In recent metro operation, however, abnormal wear has been observed with rapid material loss, atypical strip profiles, local cracks, and strong arcing. Such behavior cannot be explained by normal-wear models alone because it involves coupled mechanical, electrical, thermal, and environmental effects. This paper condenses the main findings of a full-length study and focuses on three issues: the staged evolution of abnormal wear, the factors triggering the transition, and experimental validation of the proposed mechanism.

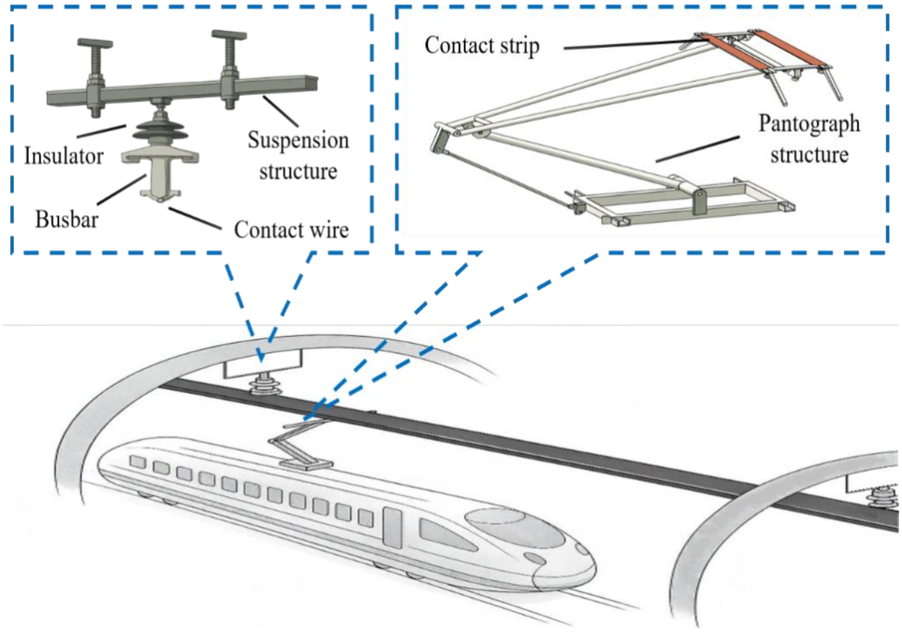

Fig 1. Rigid catenary and pantograph system

2 Methods

The study used long-term monitoring and maintenance data from Tianjin Metro Line 6, which is 43.5 km long and operates 45 six-car trains. Each train has two TSG22 pantographs and travels approximately 400 km per day. Wear of 58 pantographs was monitored using high-resolution gantry-mounted cameras at depot entrances. Three-dimensional point-cloud measurements of residual strip thickness were combined with mileage data to calculate the wear rate per 10000 km.

The dataset also included tunnel temperature and humidity, speed, pantograph-catenary voltage and current, pantograph head acceleration, contact force, and arcing events. Kendall and Spearman correlation analyses were used to identify the relationships among wear rate, arc behavior, contact force, temperature, and humidity. Representative contact-wire and contact-strip samples from normal, mild abnormal, and severe abnormal stages were examined by scanning electron microscopy and elemental analysis. Ring-on-block tests were then performed to validate the influence of relative humidity and contact force on arc discharge and material loss.

3 Results

Abnormal deterioration of pantograph strips is primarily manifested by an elevated wear rate. To characterise this behaviour, weekly wear data were collected from all operating trains on Tianjin Metro Line 6, as illustrated in Fig 4. The results reveal a significant seasonal pattern. Wear rates remain consistently low (< 2.5 mm/10 000 km) from week 16 to week 44, followed by a marked increase between weeks 44 and 52. After a sharp decline during weeks 8 to 16, a substantial surge is again observed in the first eight weeks of the year, during which wear rates exceed 10 mm/10 000 km. This recurring trend indicates a strong correlation between environmental conditions and wear behaviour, underscoring the necessity for seasonally adaptive maintenance strategies.

The pronounced fluctuations in wear rate suggest that environmental factors, particularly temperature and relative humidity, play a critical role in governing the underlying wear mechanisms. These factors influence the frictional and electrical characteristics of the pantograph–catenary interface, thereby contributing to the observed variability in wear performance.

Based on the measured wear rates, pantograph strip wear can be classified into three distinct phases: normal wear, mild abnormal wear, and severe abnormal wear. During the normal wear phase, the wear rate remains stable and generally below 2.5 mm/10 000 km, with only minor variations among different trains, reflecting a predictable and steady wear process under standard operating conditions. The mild abnormal wear phase represents a transitional regime between normal and severe wear, characterised by wear rates ranging from 2.5 to 10 mm/10 000 km. This phase is typically short-lived, often lasting no more than four weeks. In contrast, the severe abnormal wear phase is marked by persistently high wear rates exceeding 10 mm/10 000 km and can continue for approximately eight weeks.

Notably, during both abnormal wear phases, substantial inter-train variability in wear rates is observed. This inconsistency indicates that, despite nominally similar operating conditions, individual pantograph–catenary systems exhibit distinct contact dynamics and wear responses. Such variability is likely attributable to train-specific dynamic interactions and highlights the presence of complex, nonlinear degradation processes during abnormal wear. To elucidate the mechanisms governing the initiation and progression of abnormal wear, an integrated approach that combines large-scale field monitoring data with targeted laboratory analyses is therefore essential.

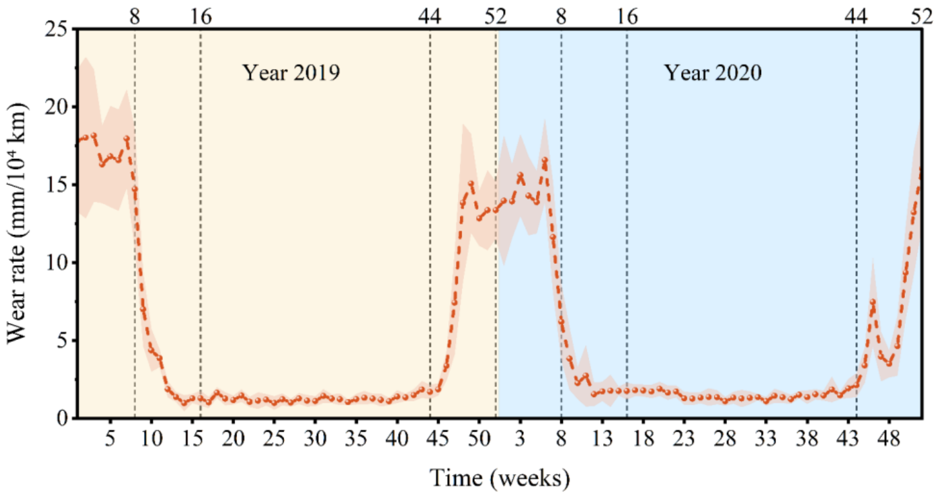

Fig 2. Weekly evolution of pantograph strip wear rate on Tianjin Metro Line 6

The wear characteristics of the contact strip, shown in Fig. 3, exhibit similarly distinct stage-dependent evolution. Macroscopically, the surface appears smooth and polished during normal wear, becomes increasingly rough in the mild abnormal phase, and exhibits significant accumulation of yellow deposits in the severe abnormal stage. Microscopic inspection reveals a predominantly smooth surface with minor shallow fissures under normal wear. Material loss becomes evident in the mild abnormal phase, resulting in isolated smooth regions. By the severe abnormal stage, the smooth surface is entirely absent, replaced by collapsed zones with pronounced yellow deposits. Detailed three-dimensional topographical analysis further shows that as abnormal wear progresses, height variations on the contact strip surface increase considerably, leading to heightened roughness and surface irregularity. This progression signifies localised material degradation and underscores the escalating damage with advancing wear.

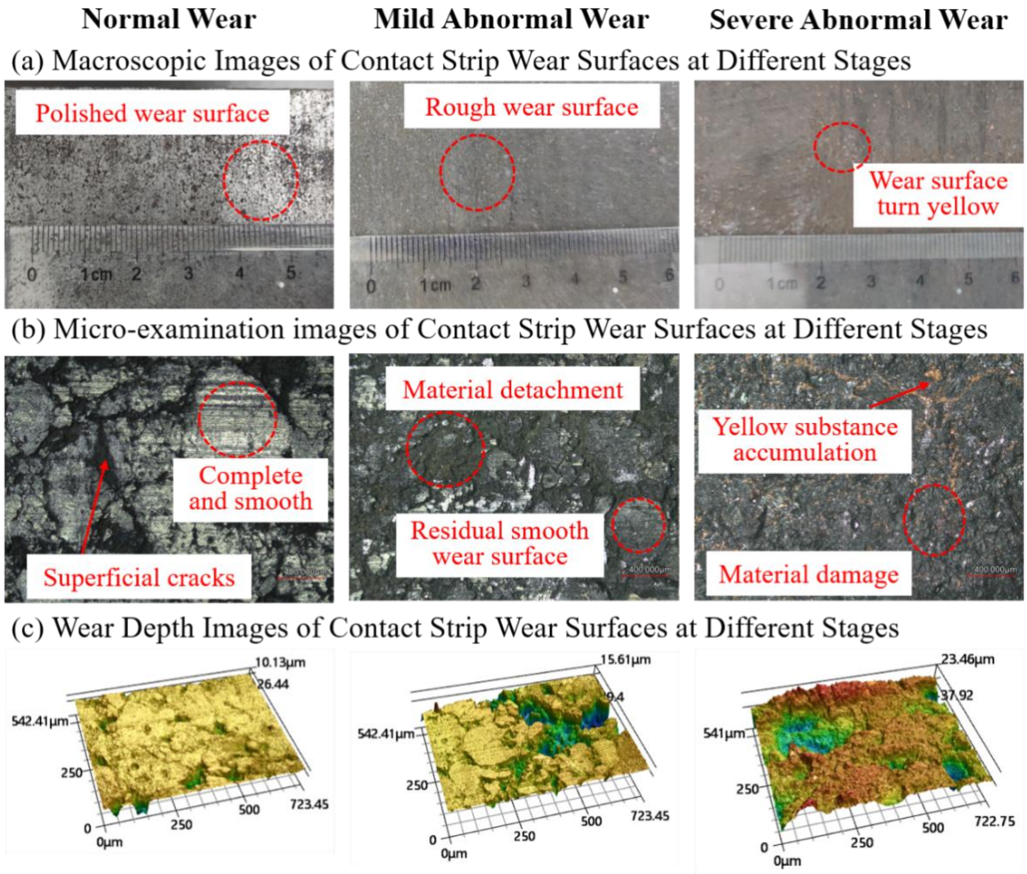

Fig 3. Contact Strip Wear Morphology at Different Stages

A comparative assessment of contact wire and contact strip morphologies reveals a clear transition from stable, controlled wear to irregular and destructive wear. For the contact wire, this transition is characterized by progressive loss of the carbon layer, proliferation of arc-ablation marks, and the evolution of wear grooves from broad and shallow to narrow and dense. In contrast, the contact strip evolves from a smooth surface to a highly roughened morphology, accompanied by material flaking and chemical deposition, ultimately leading to severe and uneven wear. These observations are corroborated by three-dimensional surface parameters, which consistently show increasing surface irregularity with wear progression. Collectively, these results demonstrate the complex interplay among mechanical wear, electrical effects, and environmental influences, underscoring the necessity of an integrated approach to understanding abnormal wear in pantograph-catenary systems.

Data from 30 train operation groups under no-arc, mild-arc, and severe-arc conditions were analyzed. Key parameter characteristics were identified, and Spearman correlation analysis was performed. The coefficient is calculated as follows:

$$\rho = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}} \tag{1}$$

where x_i and y_i represents the i-th observation of variable x and variable y, ρ represents the Spearman correlation coefficient. The value of ρ ranges from –1 to 1, with values closer to 1 indicating a stronger correlation, and the sign indicating the direction of the association.

As illustrated in the radar chart in Fig 4, mild arcs correlate strongly with low contact force and fluctuations in force and hard spots, whereas speed and current exhibit weaker correlations. Severe arcs, however, show strong correlations with current and speed, indicating that severe arcing arises under more restrictive conditions involving environmental, mechanical, and electrical coupling. Across all cases, low relative humidity and low contact pressure consistently emerge as the dominant contributors to arc initiation.

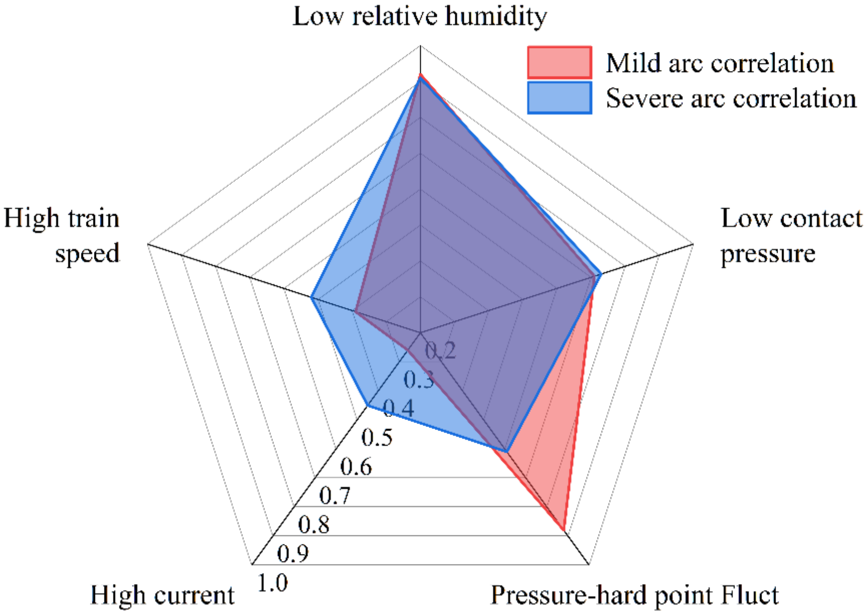

Fig 4. Radar Chart of arc-parameters correlations

4 Conclusions and Contributions

This short paper classifies metro pantograph strip abnormal wear into normal, mild abnormal, and severe abnormal stages. The key transition is controlled by carbon-film depletion, arc ablation, material transfer, low humidity, and insufficient contact force. The integration of maintenance data, microscopic evidence, correlation analysis, and controlled tests provides a compact mechanism-oriented explanation for abnormal wear.

For engineering practice, low-humidity periods should be treated as high-risk windows for inspection. Monitoring arc indicators and maintaining adequate contact force can help identify early abnormal wear before severe material loss occurs.

Acknowledgements

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