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IMPACT RESPONSES OF RAILWAY CONCRETE SLEEPERS WITH SURFACE ABRASIONS

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In reality, railway infrastructure experiences aggressive wheel-rail contacts and changing operational actions. Especially in sharp curve and high gradient, trains induce even much-more aggressive actions on the infrastructure. Our critical review reveals that railway concrete sleepers degrade over time. The ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers (especially at railseat zone). In addition, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of railseat abrasions in concrete sleepers due to the unbalanced loading conditions. Such the abrasions affect not only the wheel/rail interaction and track geometry, but they also undermine structural integrity of the track structures. The latter is by far more crucial as it underpins the public safety of railway networks. This paper presents a nonlinear finite element model of a standard-gauge concrete sleeper in a track system, taking into account the nonlinear tensionless nature of ballast support. The finite element model was validated using static and dynamic responses in the past. In this paper, the dynamic effects of surface abrasions, including surface abrasion and soffit abrasion, on the impact responses of sleepers are firstly highlighted. The outcome of this study will improve the rail maintenance and inspection criteria in order to establish appropriate and sensible remote track condition monitoring network in practice. The insight into the impact behaviour will improve predictive track maintenance scheme by properly informing track engineers to avoid costly unplanned corrective track maintenance.

Keywords: Surface abrasion, railseat abrasion, soffit abrasion, railway sleepers or cross-ties, impact behaviour, impact responses

1. Introduction

Under climate and operational uncertainties, railway tracks experience changing conditions and are exposed to changing magnitudes and directions of load burdens. Commonly, railway sleepers (also called ‘railroad tie’ in North America) are embedded in ballasted railway tracks. They are a crucial structural element to support the track structures. Their key functions are to redistribute wheel loads from the rails to the underlying ballast bed and to secure rail gauge and enable safe passages of rolling stocks. Based on the current design approach, the design life span of the concrete sleepers is aimed at around 50 years in Australia and around 70 years in Europe [1-8]. Figure

1 shows a typical ballasted railway track and their key components. There are two groups of track components: superstructure and substructure. 'Superstructure' consists of rails, rail pads, fastening systems, sleeper, under sleeper pad and ballast bed. 'Substructure' commonly refers to subballast (or called 'capping layer'), formation, bituminous layer (if any) and foundation (e.g. structural fills).

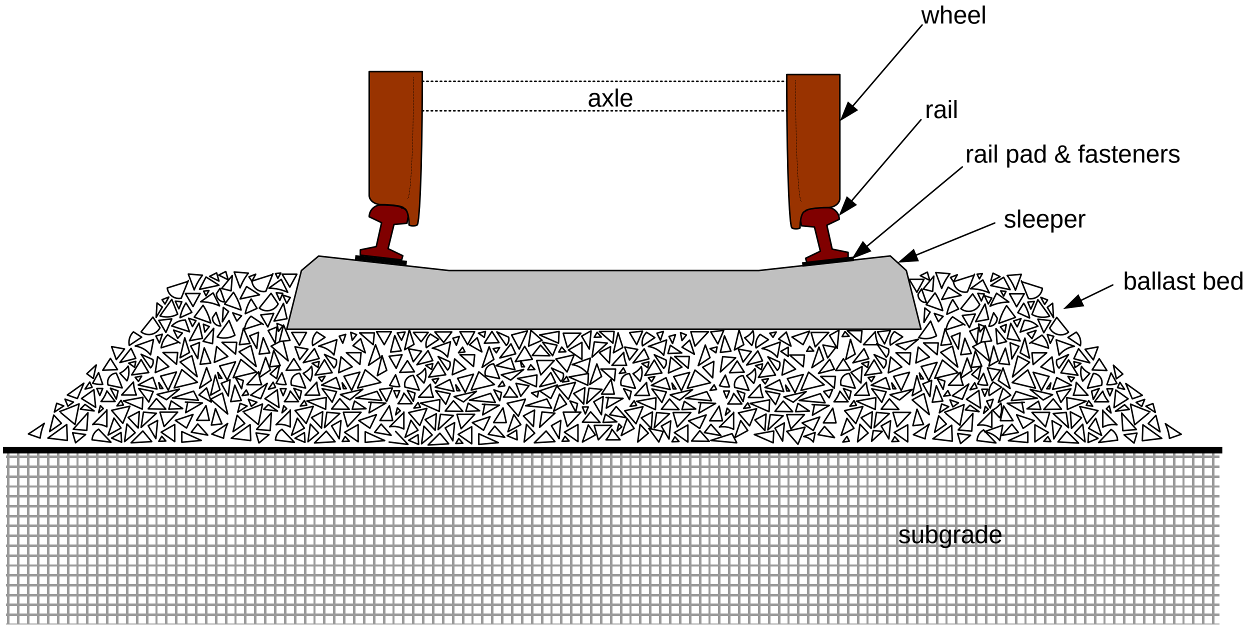
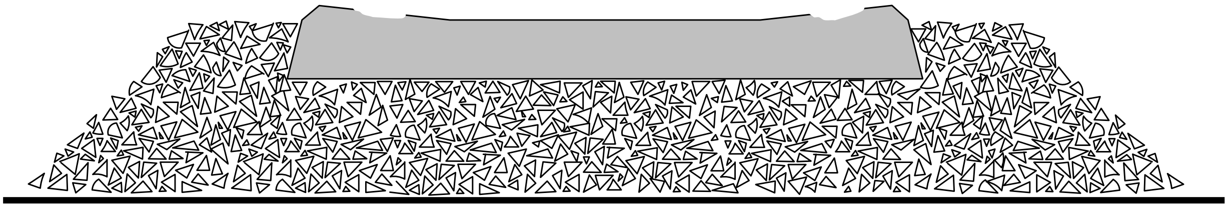


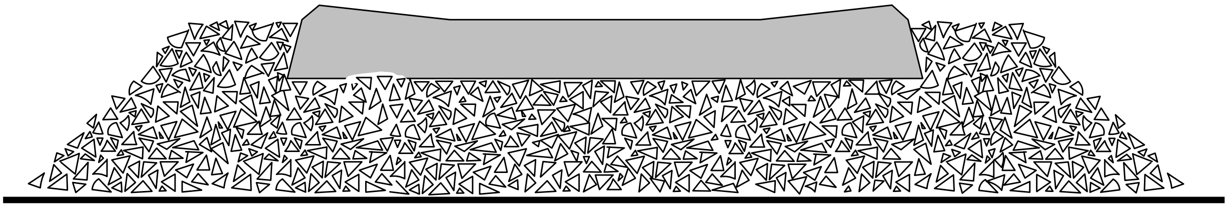
Figure 1: Typical ballasted railway track components.

To establish rational railway sleeper models, previous numerical and experimental investigations have been conducted [9-15]. The studies showed that most of the numerical and analytical models make uses of the concept of beam on elastic foundation where a sleeper is laid on the elastic support, acting like a series of springs. It is found that only vertical stiffness is sufficient to simulate the ballast support condition because the lateral stiffness seems to play an insignificant role in sleeper's bending responses [16-20]. About 5 to 15% difference was reported for vertical responses between 3D solid and 2D beam simulations depending on various track and environmental factors [21]. In practice, the lateral force is often less than 20% of vertical force and the anchorage of fastening and ballast resistance have been considered to take care of lateral actions [22-23]. In fact, field measurements suggest a diverse range of sleeper flexural behaviors, which are largely dependent on the support condition induced by ballast packing and tamping [24-28]. However, it is still questionable at large whether modern ballast tamping process is effective and it could enable adequate symmetrical support for sleeper at railseat areas. In reality, the ballast is tamped only at the railseat areas. The ballast at the mid span is intentionally left loosening, with the intention to reduce negative bending moment effect on sleeper mid span, which is the cause of centre bound. Over time, ballast densification at railseats is induced by dynamic broadband behaviours and the sleeper mid-span comes into contact or is fully supported by ballast until the track geometry is restored by resurfacing activity (i.e. re-tamping) [29-30]. At railseat, the dynamic loading condition gives a high change that the bottom of sleeper (or called 'soffit') may experience aggressive abrasive force, wearing out the materials in the region. Also, excessive mid-span contacts soffit abrasion and then often cause 'centre-bound' problem when the sleeper cracks at mid-span.

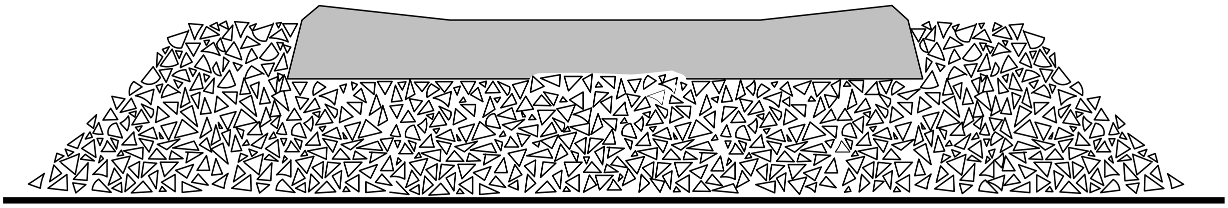
A critical literature review reveals that the impact responses of railway sleepers with surface abrasion have not been fully investigated, especially when the sleepers are deteriorated by excessive wears. Figure 2 shows the typical wears of a railway sleeper [30-34]. Most common wears are railseat abrasion, soffit abrasion at railseat and soffit abrasion at mid span. These deterioration mechanisms can be observed in the fields. Although it is clear that the railway sleepers can experience dynamic lateral wears, such the aspect has never been fully investigated in terms of structural integrity of the sleepers. This paper is to investigate and present an advanced railway concrete sleeper modelling capable of parametric analysis into the effect of surface abrasion on the dynamic behaviours of railway sleepers. The emphasis is placed on the nonlinear transient responses of the deteriorated railway concrete sleepers subjected to a spectrum of wear or abrasion at the mid span and at the railseats, in comparison with the intact railway sleepers. The findings will help improve the understanding into fundamental dynamics of damaged sleepers and pave the pathway to identify appropriate damage detection technology for railway sleepers. The insight into the impact behaviour will improve predictive track maintenance scheme by properly informing track engineers to avoid costly unplanned corrective track maintenance [35].



a) railseat abration



b) soffit abrasion at railseat



c) soffit abrasion at midspan

Figure 2: Typical surface abrasions of railway sleepers. These wears are stochastic but the concentration of surface wears can be deterministically estimated in practice [11].

2. Finite Element Modelling

Extensive studies in the past have proven that the two-dimensional Timoshenko beam model is the most suitable option (fast/efficient computing) for modeling concrete sleepers under vertical loads [2-5]. In this study, the finite element model of concrete sleeper has been previously developed and calibrated against the numerical and experimental modal parameters [25-30]. Figure 3 shows the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 [31], the numerical model of an in-situ sleeper included the beam elements, which take into account shear and flexural deformations, for evaluating the vertical responses. The trapezoidal cross-section was assigned to the sleeper elements. The rails and rail pads at railseats were simulated using a series of spring. In this study, the sleeper behaviour is stressed so that very small stiffness values were assigned to these springs. In reality, the ballast support is made of loose, coarse, granular materials with high internal friction. It is often a mix of crushed stone, gravel, and crushed gravel through a specific particle size distribution. It should be noted that the ballast provides resistance to compression only. As a result, the use of elastic foundation in the current standards in Australia and North America [1, 18] does not well represent the real uplift behaviour of sleepers in hogging moment region (or mid span zone of railway sleeper). In this study, the support condition has thus been idealised using the tensionless beam support feature in Strand7 [31]. This attribute allows the beam to lift or hover over the support while the tensile supporting stiffness is omitted. The tensionless support option can correctly represent the ballast characteristics in real tracks [31-32]. This feature creates nonlinear boundary condition scheme to the sleepers and requires iterative computation to converge the coupling ballast-sleeper deformations. Table 1 shows the geometrical and material properties of the finite element model. It is important to note that the parameters in Table 1 give a representation of a specific rail track in European condition. These data have been validated and the verification results have been presented elsewhere [25-30]. Parametric study has been carried out considering the possible cases of railseat abrasion, soffit abrasion at railseat zone and soffit abrasion at mid-sleeper region. In this study, non-linear transient analysis has been carried out using a unit sinusoidal impulse of 3 msec (100 kN) at both railseats. This impact loading is coincided with the loading due to common defects such as wheel flats. Non-dimensional analysis is then carried out to evaluate the dynamic effects of surface abrasions on the impact responses of the railway sleepers.

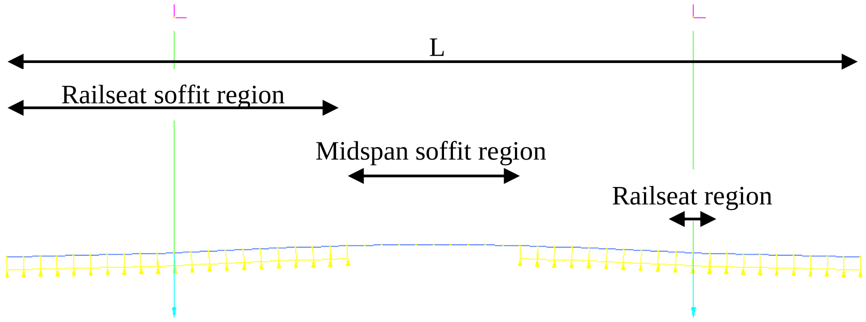


Figure 3: STRAND7 finite element model of worn concrete sleepers.

Table 1: Engineering properties of the reference sleeper used in the modelling validation

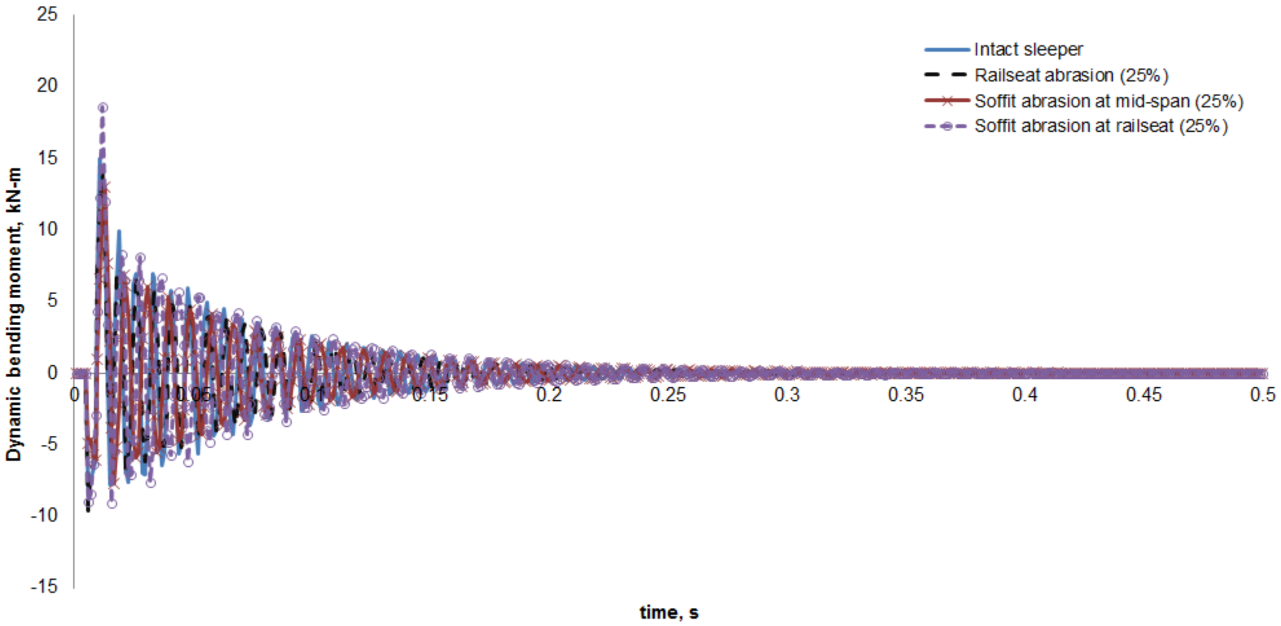
Parameter List	Characteristic value	Unit
Flexural rigidity	$EI_c = 4.60$, $EI_r = 6.41$	MN/m^2
Shear rigidity	$\kappa GA_c = 502$, $\kappa GA_r = 628$	MN
Ballast stiffness	$k_b = 13$	MN/m^2
Rail pad stiffness	$k_p = 17$	MN/m
Sleeper density	$\rho_s = 2{,}750$	kg/m^3
Sleeper length	$L = 2.5$	m
Rail-centre distance	$G = 1.5$	m
Rail gauge	$g = 1.435$	m

3. Results and Discussion

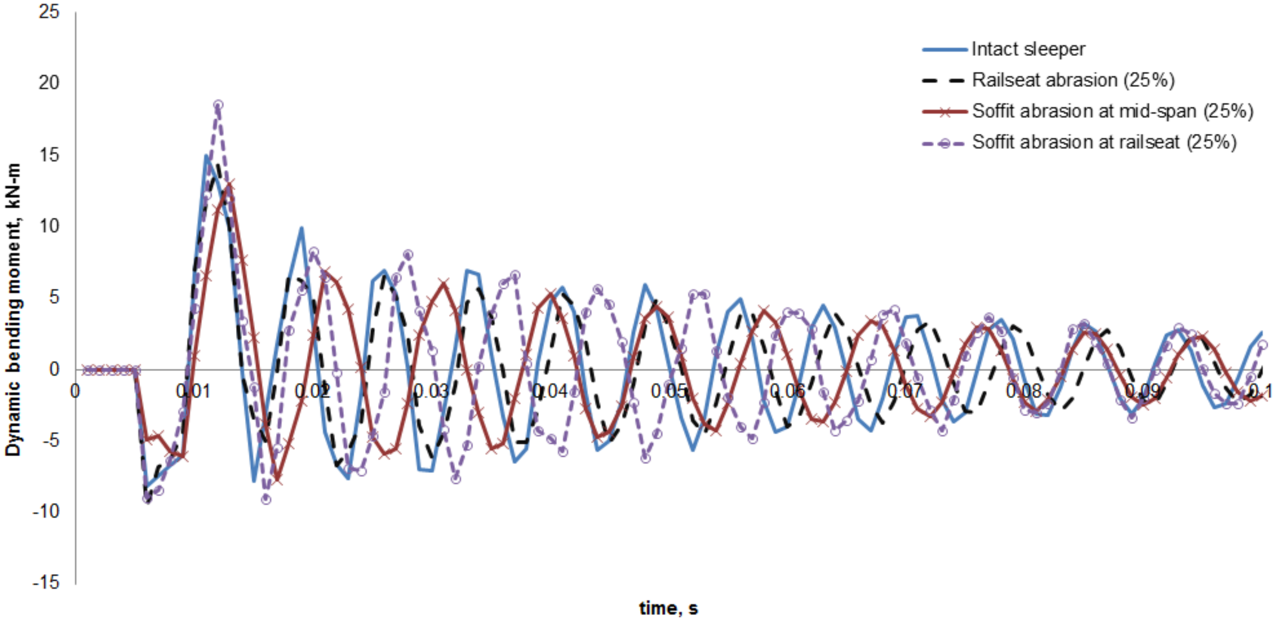
Using the design data in Table 1, the impact vibrations of the worn concrete sleepers can be illustrated in Figure 4 for railseat abrasion, soffit abrasion at railseat, and soffit abrasion at mid span, respectively. It is clear that the dynamic actions are affected by the surface abrasion. Especially, the soffit abrasion at railseat can amplify the dynamic action at the mid-span of sleepers.

3.1 Railseats Abrasion

Table 2 shows the effects of railseat abrasion on the dynamic bending moment ratios and the relative dynamic displacement responses. It is clear that the increase of railseat abrasion tends to induce softening action for positive flexure at mid-span (up to 5% reduction) whilst induce hardening action for negative bending moments (up to 17% increment). Softening actions can be observed at the railseats. The abrasion tends to increase dynamic displacements at both railseats and mid-span of the railway sleepers.



a) Responses over 0.5s



b) Responses over 0.1s

Figure 4: Dynamic actions at sleeper mid-span.

Table 2: Effects of railseat abrasions

Loss of Depth	**Bending moment ratio**				**Relative displacement (mm)**			
	Mid-span		**Railseat**		**Mid-span**		**Railseat**	
(ΔD/D)	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging
0%	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
5%	0.9033	1.0844	0.9993	0.8474	0.3700	0.0100	0.3500	0.1400
10%	0.9333	1.0501	0.9978	0.9120	0.2300	0.0100	0.2200	0.1300
15%	0.8833	1.0844	0.9978	0.8456	0.3600	0.0090	0.3500	0.1400
20%	0.9253	1.1222	0.9935	0.7738	0.4800	0.0075	0.4800	0.1480
25%	0.9533	1.1699	0.9855	0.6822	0.5900	0.0040	0.6100	0.1520

Table 3: Effects of soffit abrasion at mid-span

Loss of	**Bending moment ratio**				**Relative displacement (mm)**			
Depth	**Mid-span**		**Railseat**		**Mid-span**		**Railseat**	
(ΔD/D)	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging
0%	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
5%	0.9027	1.0648	1.0051	0.9443	0.3300	0.0300	0.3200	0.1300
10%	0.8873	0.9438	1.0109	0.8797	0.6800	0.0500	0.6600	0.1400
15%	0.8673	0.7873	1.0159	0.8205	0.9500	0.0600	0.9600	0.1500
20%	0.8667	0.7531	1.0217	0.7576	1.2700	0.0700	1.2600	0.1600
25%	0.8653	0.7384	1.0282	0.6894	1.5600	0.1600	1.5500	0.1800

Table 4: Effects of soffit abrasion at railseats

Loss of	**Bending moment ratio**				**Relative displacement (mm)**			
Depth	**Mid-span**		**Railseat**		**Mid-span**		**Railseat**	
(ΔD/D)	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging	Sagging	Hogging
0%	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
5%	0.9600	1.0257	0.9877	0.9713	0.5500	0.0500	1.0700	0.0700
10%	0.9733	1.0501	0.9725	0.9300	1.2300	0.0900	2.2900	0.1600
15%	1.0520	1.0709	0.9573	0.8833	1.9000	0.1300	3.4500	0.2400
20%	1.1433	1.0868	0.9407	0.8600	2.5500	0.3300	4.6300	0.3300
25%	1.2413	1.1112	0.9204	0.7576	3.3800	0.4100	2.8800	0.4300

3.2 Soffit Abrasion at a Railseat region

Table 3 presents the effects of soffit abrasion at the mid-span of sleepers on the flexure and relative dynamic displacements. It is very clear that the railseat abrasion slightly increases the bending moment but significantly amplifies dynamic responses at both railseats and mid-span.

3.3 Soffit Abrasion at Mid-span region

From Table 4, it can be seen that the soffit abrasion at railseats can affect the mid-span bending moment significantly (up to 24% increase in bending moment). This implies that center-bound failure of sleepers could be potentially induced. The soffit abrasion also significantly impact the dynamic displacements at both railseats and mid-span.

4. Conclusion

In the field, railway infrastructure and its components experiences harsh environments and aggressive loading conditions from increased traffics and load demands. A wide variety of factors has influences on the rate of deterioration of track components. It is reported that the ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers (especially at railseat zone). Furthermore, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of railseat abrasions in concrete sleepers due to the unbalanced loading conditions. This study has established a calibrated finite element model of a standard-gauge concrete sleeper in a track system, capable of capturing the tensionless nature of ballast support and evaluating the dynamic behaviour of the worn sleepers. It highlights the influences of surface abrasions, including surface abrasion and soffit abrasion, on the impact behaviours of sleepers. The results exhibit that soffit abrasions at both railseats and mid-span induce dynamic hardening phenomena of the concrete sleepers. This soffit abrasion should thus be monitored and inspected regularly (e.g. once in 5 years). This insight will improve the rail maintenance and inspection criteria in practice.

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