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Derailment Risk Assessment of a Freight Wagon due to Cyclic Top

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Abstract

Railway network infrastructure managers ensure safe operations by inspecting and maintaining tracks, adhering to regulations. Track quality is assessed post-inspection, processing track irregularities according to standards. Despite tracks meeting quality criteria, some freight wagon derailments occur. Derailment reports cite cyclic top as an irregularity not covered by standards as the cause of the derailments, however, no clear method to quantify it is provided. This paper aims to develop a robust method for identifying cyclic top. This work considers case studies involving a freight train model from a previous derailment in Portugal and suspected cyclic top track segments. Multibody simulations are performed not only to assess vehicle-track interaction under various conditions, identifying high derailment risk cases using unloading derailment indicators, but also to determine wagon pitch and bounce natural frequencies. Results show a good correlation between high derailment risk, the natural frequencies of the vehicle and the most important frequencies of the track irregularities, which strongly depend on vehicle speed. Thus, it is designed an algorithm to identify cyclic patterns based on track irregularities that is usable by infrastructure managers.

Keywords: railway vehicle dynamics, infrastructure, track irregularities, multibody dynamics, wheel-rail contact, unloading indicator.

1 Introduction

One significant yet often underrecognized issue in railway safety is the presence of cyclic top defects on tracks. These defects are a series of regular dips on the track that can drastically compromise the stability of trains and potentially lead to derailments. Despite their severe impact, cyclic top remains out from standard and the current descriptions are vague and questionable. Traditional approaches, primarily reliant on visual inspections and basic monitoring techniques, often fail to capture these defects at an early stage and lack effectiveness. While visual identification is possible, it is not feasible as a comprehensive solution due to the impracticality of examining all existing tracks in detail.

Track irregularities, which are vertical and horizontal deviations of the rail from the design layout, are present in any track and appear due to imperfect installation, track usage, or environmental influences. The track irregularities are monitoring according to the inspection schedule that is decided by the infrastructure managers as it critically impact the vehicle’s stability and increase the likelihood of derailment. From the inspections, six track irregularities are measured, the longitudinal level of the left and right rails, the alignment level of the left and right rails, and the gauge and cant deviations [1]. These elements are integral to the track model, emphasizing the dynamic interaction between the vehicle and its operating environment [2].

This work focuses primarily on cyclic top defects, which is not covered in the current standards, including the EN 13848 [3]. Nonetheless, derailment reports, generally describe cyclic top as a vertical irregularity that can develop due to repeated stress cycles caused by the passing of trains. They are characterized by repeated depressions and material deformations on the rails, typically appearing in short, regular intervals, which may not be immediately visually obvious because of voiding under sleepers. Experts have analyzed derailments caused by these defects [4–7] and pointed out that the cyclic top had been exacerbated by insufficient maintenance practices and the lack of early detection techniques. Detecting track defects early enables operating companies to strategically manage the time maintenances, thereby minimizing disruptions to transportation services. Traditional rail inspection methods were not always capable of identifying the early stages of these defects.

2 Derailment due to Cyclic Top

The cyclic top defect has been implicated in several railway derailments along the years. Its identification and management are particularly challenging, which is why it has been underrepresented in established industry standards. Cyclic top has been described as a series of regular longitudinal irregularities on the track, which result in periodic deviations in rail level. As illustrated in Figure 1, this phenomenon creates alternating high and low points across the track, maintaining a consistent magnitude and patterning that can significantly affect railway vehicle dynamics [4,5,7].

To fully comprehend the cyclic top defect, derailment incidents associated with this defect reported by recognized authorities are analyzed in this work. These incidents include a freight train derailment at Marks Tey, Essex in June 2008 [6], another incident at Castle Donington, Leicestershire in January 2013 [4], a derailment near Gloucester in October 2013 [5], and another in Portugal in November 2015 [7]. These incidents were extensively analyzed and reported by the Rail Accident Investigation Branch (RAIB*)* from the UK and the homologous institution in Portugal GPIAAF.

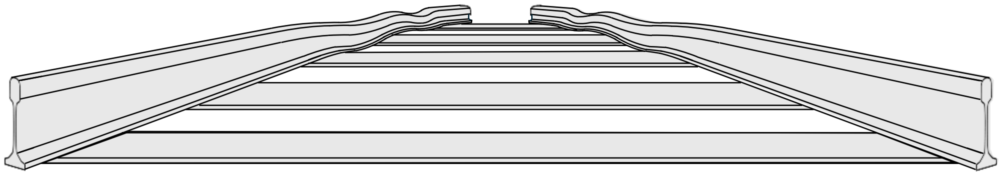

Figure 1: Cyclic top defect.

Upon thorough analysis, it is noticeable that there are several similarities among the derailments that resulted from cyclic top. Each scenario offers useful insights into the difficulties this issue presents and the intricacies of dealing with this defect in the context of railway infrastructure.

The post-derailment investigations turn out to be essential for understanding the dynamics and factors leading to these accidents. Moreover, these derailments share the following traits in common:

- Identification of cyclic top based on visual inspection or track measurements.
- Insufficient incorporation of cyclic top defect management in industry standards [8,9].
- Examination of longitudinal rail leveling patterns to identify potential cyclic top defects.
- Influence of vehicle speed and suspension characteristics on worsening cyclic top effects.
- Alignment of excitation frequencies generated by the cyclic top with resonant frequencies of the wagon's motion, leading to wheel unloading.
- Alignment of the distance between the center of bogies with common wavelengths of cyclic top.
- Heightened risk of derailment in partially loaded or tare conditions due to variation in suspension stiffness.
- Need for a comprehensive risk mitigation measures and enhanced railway safety standards.

3 Vehicle-Track Interaction Analysis

In railway vehicle dynamics, multibody dynamics is used to simulate the vehicle-track interaction. The simulation consists of three models: the vehicle model, the track model, and the vehicle-track interaction model [10]. These models are integrated to form a complete railway system. Figure 2 demonstrates a representation of the vehicle model running on a track in a multibody simulation.

The track model is developed based on the dataset of a railway track. The dataset included track layout, and the track irregularities previously recorded by the inspection vehicle EM120. The output of a multibody simulation provides a comprehensive account of the dynamic behavior exhibited by the vehicle's components throughout the analysis period, presenting detailed information on the forces at the wheel-rail contact points. For straight segments, the ratio $\Delta Q/Q$ is the key indicator of derailment risk, which is the indicator used in this work since cyclic top is characteristic of straight segments. This parameter quantifies the percentage of vertical wheel force that unloads during operation. The $\Delta Q/Q$ indicator is given by

$$\frac{\Delta Q}{Q} = \frac{Q_{stat} - Q}{Q_{stat}} \tag{1}$$

where Q_{stat} is the wheel static vertical load and Q is the vertical wheel load that is obtained through the multibody simulations.

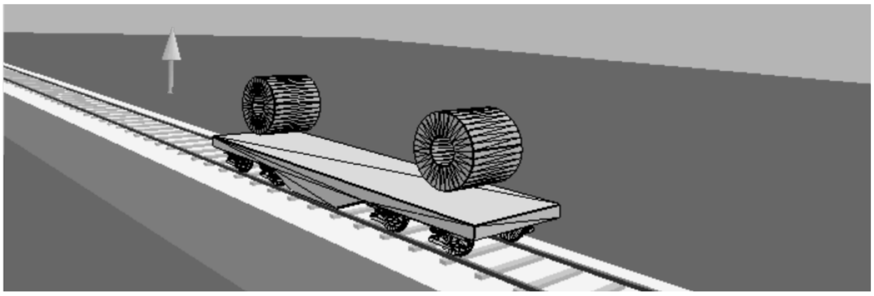

Figure 2: Multibody simulation of a railway vehicle running on a track.

The received data describes a track segment consisting of four curves and four straight sections, as shown in Figure 3. Given that cyclic top irregularities are primarily vertical deviations observed in straight-track segments, the analysis was specifically focused on these areas. The four straight segments (a), (b), (c) and (d) presented in Figure 3, are separately analysed.

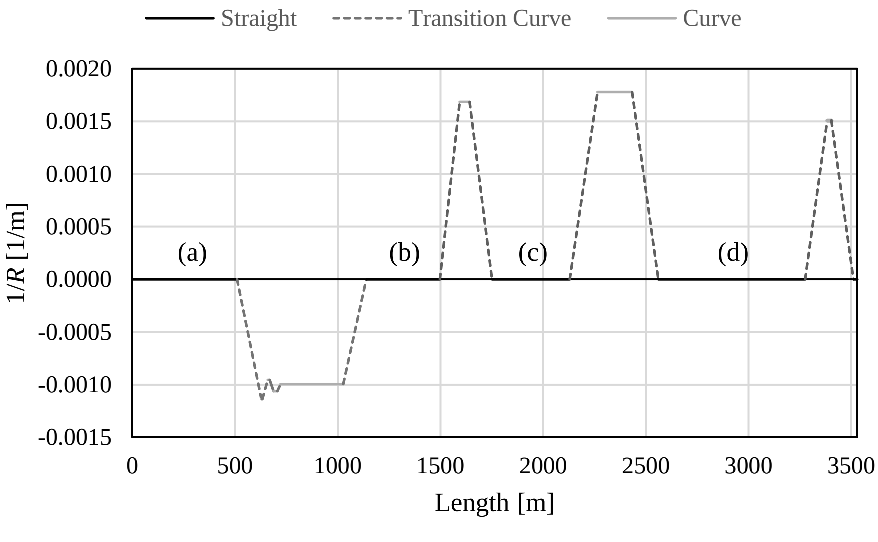

Figure 3: Division of track irregularities in straight segments (a), (b), (c), and (d).

Several MBS are tested to identify in which conditions the vehicle run in higher and lower risk of derailment. The four straight track sections, labeled (a), (b), (c), and (d), presented in Figure 3, are considered. The vehicle speed is varied from 50 km/h to 100 km/h, increasing in increments of 10 km/h, where 100 km/h is the maximum allowed speed. The vehicle's cargo, which critically influences its dynamic behavior, is modeled under both loaded and unloaded conditions.

Observations are carried out under both loaded and unloaded conditions at the maximum operational speed of 100 km/h for all track segments. However, Figure 4 specifically illustrates the initial phase of the dynamic analysis of section (c), which focused on the behavior of a specific wheel, which in this case is the rear right wheel of the rear wheelset, in terms of the *ΔQ/Q*. From various scenarios, this wheel shows one of the most critical behaviors across all wheels, thereby serving as a representative for assessing the general behavior in each track section at a critical velocity.

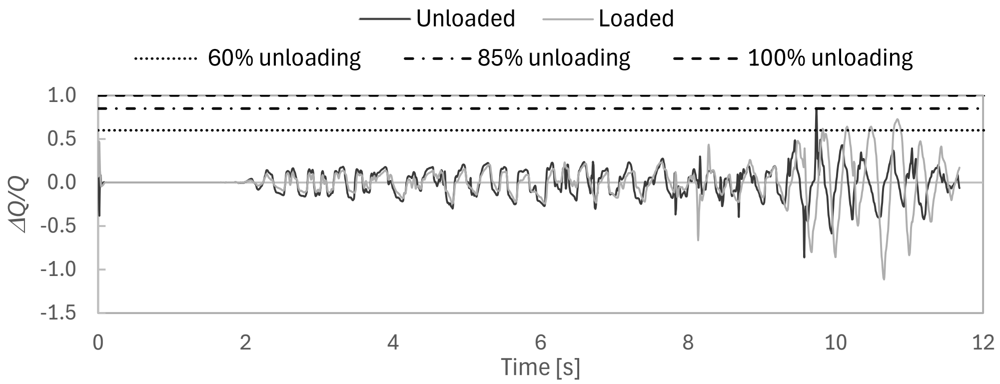

Figure 4: *ΔQ/Q* obtained for the right wheel of the rear wheelset on track (c).

In the graph of section (c), shown in Figure 4, when the vehicle travels at 100km/h, a distinct pattern appears, especially towards the end of the time scale. Under both loaded and tare conditions, the *ΔQ/Q* parameter reveals a consistent increase in magnitude. This regularity could be indicative of a cyclic pattern of track features or a resonant interaction between the vehicle and the track.

The standardized limit for the *ΔQ/Q* parameter is 60% [8], however, some studies suggest a higher permissible limit for unloading, set at 85% [9]. The evaluation of the *ΔQ/Q* parameter along the track length categorizes the risk of derailment into several intervals:

- *ΔQ/Q* < 60%: wheels are considered safely loaded within this range, posing a minimal risk of unloading.
- 60% < *ΔQ/Q* < 85%: there is a heightened risk of derailment compared to the previous range, indicating more significant unloading.
- 85% < *ΔQ/Q* < 100%: This interval represents the highest risk of derailment, with wheels nearing critical unloading conditions.
- *ΔQ/Q* = 100%: At this level, the wheel is completely unloaded, signaling an immediate and extreme risk of derailment in real operations.

An analysis method has been implemented to identify the peaks in the graphs of *ΔQ/Q* over time for each of the vehicle's wheels. The identified peaks provide precise coordinates corresponding to the track location and its associated *ΔQ/Q* value. By cataloging the number of peaks within the predefined intervals, which are 60% < *ΔQ/Q* < 85%, 85% < *ΔQ/Q* < 100%, and *ΔQ/Q* = 100%, for the graphs of all wheels, the method yields a quantitative assessment of unloading events. Table 1 presents the color scheme of the *ΔQ/Q* intervals representing the unloading risk each multibody simulation reaches, and Table 2 presents the number of unloading occurrences in each derailment risk interval for section (c).

ΔQ/Q intervals		
60% < *ΔQ/Q* < 85%,	85% < *ΔQ/Q* < 100%	*ΔQ/Q* = 100%

Table 1: Color scheme for identification of *ΔQ/Q* risk interval.

		Loaded						Tare					
		Velocity [km/h]						Velocity [km/h]					
		50	60	70	80	90	100	50	60	70	80	90	100
ΔQ/Q Interval	[0.60, 0.85[	0	0	0	0	21	21	3	2	5	4	10	5
	[0.85, 1.00[	0	0	0	0	0	0	1	3	2	0	1	1
	= 1.00	0	0	0	0	0	0	0	0	1	1	0	3

Table 2: Number of peaks per interval of *ΔQ/Q* graphs of track section (c).

-		Loaded						Unloaded					
		Velocity [km/h]						Velocity [km/h]					
		50	60	70	80	90	100	50	60	70	80	90	100
ΔQ/Q Interval	≥ 0.60	0	0	0	0	14.1	14.4	3.2	3.9	6.5	3.6	7.8	7.7
	≥ 0.85	0	0	0	0	0	0	0.9	2.7	2.9	1.0	0.9	4.1
	= 1.00	0	0	0	0	0	0	0	0	1.0	1.0	0	3.2

Table 3: Sum of peak values per interval pf DQ/Q graphs of track section (c).

While the number of occurrences provides insights into potential unloading events, it lacks depth in terms of the degree of these events. To address this limitation, the method is augmented with a cumulative approach, aggregating the magnitudes of peaks found within critical *ΔQ/Q* intervals. This approach includes:

- Sum of *ΔQ/Q* > 60% - A holistic measure of all potential derailment events.
- Sum of *ΔQ/Q* > 85% - Reveals very high-risk unloading events, indicating areas needing urgent preventive measures.
- Sum of *ΔQ/Q* = 100% - Identifies the total number of complete wheel unloading occurrences, representing an extreme risk identification.

By extending the accumulation of peak values beyond the predefined intervals of the counting method, the analysis avoids a fragmented view of the risk. Table 3 provides a continuous spectrum of potential risk from the initial safety threshold (60 %) to the ultimate scenario of complete unloading (100 %) of section (c).

Section (c) is expressed in Table 2 for both loaded and tare conditions. In loaded conditions, sections (c) show a high number of occurrences at 90 km/h and 100 km/h, while, in tare conditions, there is a significantly increased risk of wheel unloading. This section reveals that across all velocities, when the vehicle is unloaded, the $\Delta Q/Q$ parameter reaches at least the 0.85 threshold, and, for speeds of 70, 90 and 100 km/h, it reaches full wheel unloading, demonstrating signs of high risk of derailment. This persistent wheel unloading across all velocities is consistent with the analysis of the graph in Figure 4 which shows regular peaks exceeding the unloading limits.

In addition, natural frequencies of the vehicle are inherent properties of the vehicle's structure, influenced by its mass distribution, stiffness, and damping characteristics. Multibody simulations of the vehicle with an initial perturbation are performed to promote the pitch and bounce motions, which are the most important motions in derailments of tracks with cyclic top. Multibody simulations help to identify the natural frequencies for the respective movements.

The repetitive nature of cyclic top defects can lead to resonance within the vehicle's bounce and pitch dynamics. Such resonance can significantly amplify the vehicle's response to these track defects, increasing the risk of derailment.

Bounce movement simulations begin with an initial vertical velocity applied to the vehicle body, described in Figure 5 (a), while pitch movement simulations apply an initial vertical velocity to one of the bogies, as presented in Figure 5 (b). Note that in these simulations, wheelsets are totally locked with a rigid kinematic constraint. These simulations could be easily replicated in real life by lifting the vehicle body, and lifting one of the bogies of the carbody, representing Figure 5 (a) and (b), respectively.

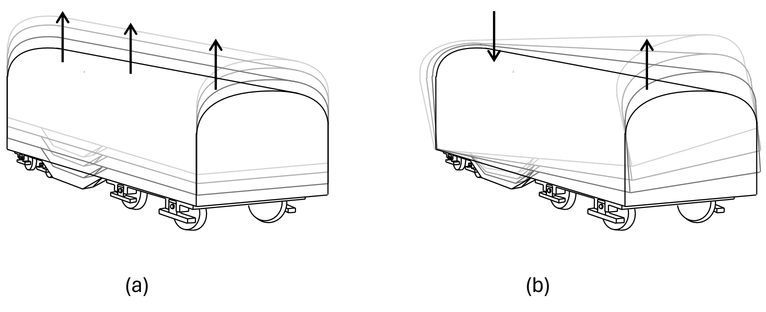

Figure 5: Vehicle initial movement of (a) bounce and (b) pitch.

The vertical coordinate, z, and the pitch angular velocity, ω_y, of the vehicle body and bogie frames are particularly significant in scenarios involving cyclic top defects, where vertical oscillations can lead to amplified dynamic responses if they resonate with the vehicle's natural frequencies. The pitch movement analysis relies on both z and ω_y parameters to represent the vehicle's rotational dynamics. However, for the bounce movement, z alone is pertinent for analysing the most important oscillations of the vehicle, since the amplitude of the relevant frequencies of the ω_y parameter do not have a sufficient amplitude to be considered.

To transition from a time-domain analysis to the frequency-domain, a Fast Fourier Transform (FFT) is employed on the data. This method enables the isolation and identification of the vehicle's natural frequencies, particularly within the frequency range of interest for freight trains which is typically below 20 Hz. The relevant frequencies from the peaks found in the FFT graphs of the z-coordinate and w_y are displayed in Tables 4 and 5, respectively.

	Loaded		Tare (Unloaded)		
	Bounce	Pitch	Bounce	Pitch	
Vehicle Body	2.94 Hz	2.33 Hz	3.84 Hz	1.00 Hz	3.20 Hz
Bogie 1	2.94 Hz	2.33 Hz	3.84 Hz	1.00 Hz	3.33 Hz
Bogie 2	2.94 Hz	2.80 Hz	3.84 Hz	-	3.53 Hz

Table 4: Vehicle's natural frequencies from z-coordinate.

	Frequencies [Hz]	
	Loaded	Unloaded
Vehicle Body	2.93	3.53
Bogie 1	2.96, 11.80, 16.60	3.87
Bogie 2	6.40, 8.46, 10.79, 12.92, 15.79	4.27, 9.20, 12.06, 18.60

Table 5: Vehicle's natural frequencies from w_y.

The range of natural frequencies observed in Tables 4 and 5 spans from 2.33 Hz to 2.96 Hz when loaded, and both bogies display a higher spectrum of frequencies, suggesting the presence of multiple vibrational modes. In tare conditions, Tables 4 and 5 observed relevant frequencies predominantly in the interval between 3.20 Hz and 3.87 Hz., and the non-excited bogie, which is designated by Bogie 2, presents a wider frequency range from 4.27 Hz to 18.60 Hz.

These frequencies align closely with the natural frequencies for vertical vibration modes of European wagons with Y25 bogies, as established by the D-RAIL research project [11]. The recognized frequencies ranged from 2.2 Hz to 2.8 Hz in fully loaded wagons, and from 3.0 Hz to 3.8 Hz in unloaded wagons, which validates the dynamic model used in this analysis. Moreover, a frequency of 1 Hz emerges in the tare condition, which may have potential implications for the vehicle's dynamic behavior.

4 Track Irregularities Analysis

The track geometry data for four straight segments, labeled from (a) to (d), are individually analyzed at the longitudinal level. The track irregularities given as function of the track length, L_{trk}, is converted into the time domain, t_{irr}, considering different vehicle speeds, v_{veh}, ranging from 50 km/h to 100 km/h, in increments of 10 km/h.

This approach produces time-domain profiles of the track irregularities, which are then subjected to FFT to examine the frequency domain characteristics. Figures 6 and 7 show the frequency responses for the right and left rails of the track section (c) at 100 km/h and 50 km/h, respectively, and the intervals of natural frequencies found in both loading conditions.

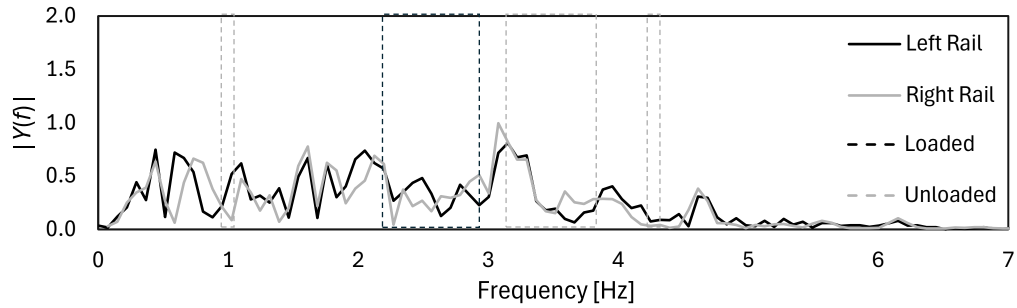

Figure 6: Section (c) frequency response at 100 km/h.

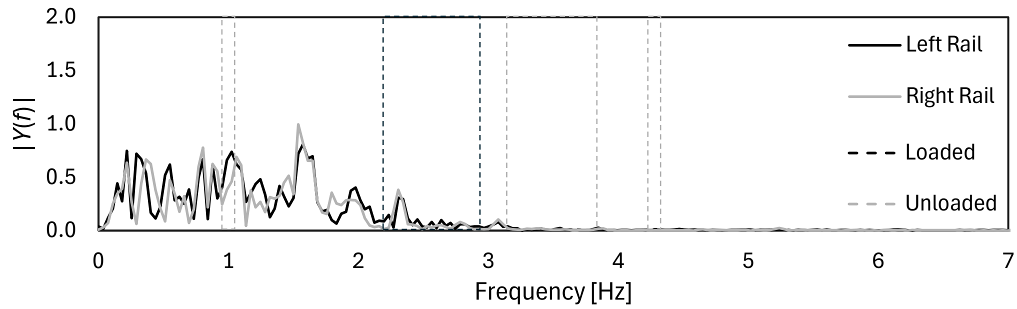

Figure 7: Section (c) frequency response at 50 km/h.

For section (c), frequency peaks at higher velocities, depicted in Figure 6, imply multiple potential resonant interactions with the vehicle. The graph for 50 km/h, presented in Figure 7, displays fewer significant peaks at higher frequencies. Yet, the lower frequency peaks still align with some of the vehicle's natural vibrations, presenting potential resonance risks. Notably, within the frequency spectrum for unloaded conditions, the track's relevant frequencies at lower velocities predominantly resonate at the vehicle's 1 Hz natural frequency.

The alignment of the natural frequencies of the vehicle with the relevant frequencies of track section (c) implies a potential for resonance, and, consequently, a high risk of derailment. This high risk of derailment is verified in both loaded and unloaded conditions, as shown in Tables 2 and 3. Especially in tare conditions, the $\Delta Q/Q$ parameter continues to demonstrate a high derailment risk across all velocities.

Various derailment reports identify cyclic top defects as a significant cause of derailments. However, these defects are not clearly defined, making it difficult to detect them from track data. This section proposes an explicitly described and explored new method to better differentiate cyclic top defects from other more common track irregularities.

In the analysis of the 2015 derailment in Portugal [7], the identified dips in the track revealed similarities in wavelengths and amplitudes in an excerpt of the longitudinal level data, and the average distance between peaks closely matches the bogie center distance for that specific vehicle.

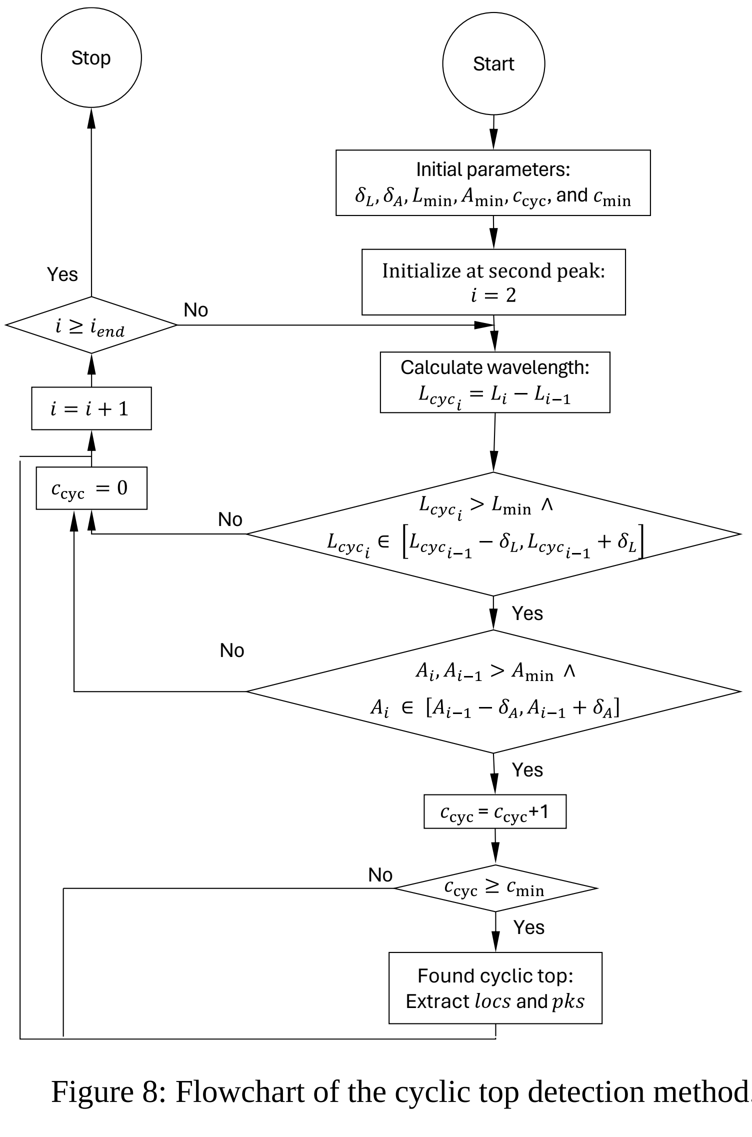

Figure 8: Flowchart of the cyclic top detection method.

The proposed method for identifying cyclic top defects involves independently analyzing the periodicity of irregularities in both left and right rails. This method focuses on identifying relevant peaks and discarding those not considered part of the pattern. The flowchart presented in Figure 8 presents a logical sequence for the identification of cyclic top defects.

This method is applied to the four track segments under study, with only section (c) showing signs of cyclic top. Figure 9 illustrates the series of peaks that indicate a cyclic top across both rails. The quasi-sinusoidal shape observed in this area confirms the cyclic nature of the defect, which is distinct from other track sections that display a more random profile.

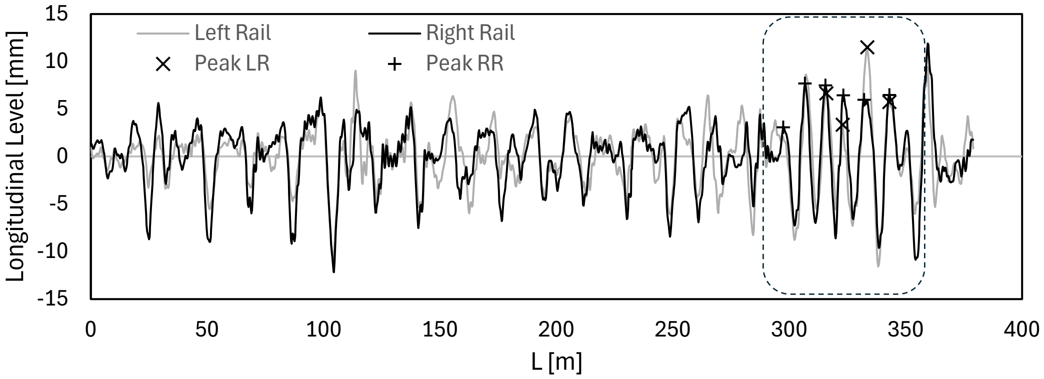

Figure 9: Cyclic top detected at the end of track section (c).

The cyclic top detection method catalogs the peak amplitudes and the distances between them, confirming that the detection conditions are met, as reported in Table 6, allowing for an analysis of the pattern's periodicity. Table 6 provides a comparative analysis of the amplitude and wavelength of the 4 peaks identified as cyclic top on the left rail and the 6 peaks on the right rail.

	Left Rail				Right Rail					
Peak ID	i	i+1	i+2	i+3	i	i+1	i+2	i+3	i+4	i+5
Amplitude [mm]	6.64	3.36	11.48	5.74	3.12	7.7	7.5	6.45	6.05	6.48
Wavelength [m]	7	10.5	9.5		9.25	8.75	7.75	8.75	11	

Table 6: Cyclic top peak information.

The average amplitude of peaks on the left rail is 6.72 meters and on the right rail is 6.22 meters, indicating a generally consistent amplitude across the track. This value is also one of the most critical amplitude values considered in Portugal's derailment report [7].

In terms of wavelength, the average for the left is 9 meters and for the right is 9.1 meters. These values are notably close to the typical bogie center distance of certain wagons. The fact that the average wavelength, which is 9 meters, is exactly 1.5 times the bogie distance of 6 meters, suggests that it can result in an out-of-phase condition. For instance, as the front bogie experiences a peak, the rear might be positioned on the ascending or descending slope of the waveform.

5 Conclusions and Contributions

This work proposes a new algorithm that identifies cyclic top by solely post-processing the track irregularities, namely, the longitudinal level. Hence, this methodology can be independently used by the infrastructure manager. Nonetheless, this methodology is developed inspired on a wide range of multibody simulations that examines the potential risk of derailment identical to the ones reported in [7], [4], [5] and [6]. Acknowledging that it is impractical performing the work carried out for all freight vehicles that operate in a railway network, it is proposed algorithm that considers the track geometry and the findings obtained from this work. This innovative algorithm identifies cycles of similar wavelengths, has proven invaluable. It successfully identified a cyclic pattern in a track segment, under the specified criteria, that was previously noted for regular unloading patterns at certain velocities.

Acknowledgements

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