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SIMULASI DINAMIKA BENDA JAMAK INTERAKSI RODA-REL UNTUK LOKOMOTIF LANGSIR DI JALUR BERPUNTIR

MULTIBODY DYNAMICS SIMULATION OF WHEEL-RAIL INTERACTION FOR A SHUNTER LOCOMOTIVE ON A TWISTED TRACK

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Abstrak

Dampak puntiran rel terhadap lokomotif shunter, yang lebih jarang diteliti dibandingkan dengan kereta kecepatan tinggi dan kereta barang, dianalisis untuk memperluas pengetahuan tentang interaksi roda-rel. Studi ini berfokus pada pengaruh puntiran rel sebesar 5% terhadap gaya pegas yang dialami oleh roda kereta, dengan menyoroti isu-isu utama seperti potensi anjlok dan hilangnya kontak roda-rel. Dengan menganalisis rasio Nadal dan pengangkatan roda (wheel lift) dalam kondisi kecepatan rendah (10-20 km/jam) yang khas untuk lokomotif shunter, studi ini memberikan wawasan baru tentang keselamatan operasional. Simulasi dinamika multibodi menggunakan model lokomotif dua gandar sederhana menunjukkan bahwa, meskipun dalam kondisi puntiran rel yang menantang, rasio Nadal dan pengangkatan roda tetap berada dalam batas aman, mengindikasikan risiko anjlok yang rendah. Meskipun temuan ini sejalan dengan kriteria keselamatan yang ditetapkan untuk jenis kendaraan rel lainnya, fokus pada lokomotif shunter dalam kondisi tersebut merupakan kontribusi baru yang mengisi kesenjangan dalam literatur yang ada. Keterbatasan studi ini, termasuk penyederhanaan model dan pengecualian kompleksitas dunia nyata, menyoroti perlunya validasi lebih lanjut dan penelitian untuk meningkatkan pemahaman tentang dinamika roda-rel dalam berbagai kondisi operasional.

Kata Kunci: Rel Kereta Api, Anjlok, Dinamika Multibodi, Rasio Nadal, Roda Rel

Abstract

The effects of track twist on a shunter locomotive, a subject less explored compared to high-speed and freight trains, are investigated to extend knowledge of wheel-rail interaction. The study focuses on the impact of a 5% track twist on spring forces experienced by train wheels, addressing key issues such as derailment potential and wheel-rail contact loss. By analyzing the Nadal ratio and wheel lift under low-speed conditions (10-20 km/h), typical for shunter locomotives, the study provides new insights into operational safety. Multibody dynamics simulation with a simplified two-axle locomotive model shows that, despite challenging twisted track conditions, both Nadal ratio and wheel lift remain within safe limits, indicating a low risk of derailment. While these *findings align with safety criteria established for other types of rail vehicles, the focus on shunter locomotives under such conditions represents a novel contribution to the field, filling a gap in existing literature. The study's limitations, including model simplifications and the exclusion of real-world complexities, highlight the need for further validation and research to improve understanding of wheel-rail dynamics across varied operational environments.*

Keywords: *Rail Track, Derailment, Multibody Dynamics, Nadal ratio, Rail Wheel*

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INTRODUCTION

Railway systems are integral to modern transportation, offering both efficiency and reliability for moving passengers and freight[1]. However, maintaining this reliability is a complex challenge, particularly in relation to train derailments, which can have severe economic and safety repercussions[2-4]. Understanding the dynamic interactions between trains and tracks, and how these interactions affect safety, is crucial for advancing railway infrastructure[5].

This study focuses on the dynamic interaction between wheels and rails, particularly in the context of track twists, which play a significant role in derailments. Derailments can arise from various factors including track irregularities, inadequate maintenance, and structural failures. Research into the causes of major train derailments reveals that track issues, such as twists and misalignments, are significant contributors[6]. Studies on shunt vehicle derailments and other specific incidents provide insights into these failure mechanisms and their impact on safety[7-8]. Additionally, empirical analyses have highlighted differences in derailment rates across different types of trains, emphasizing the need for targeted safety measures[9].

Track irregularities, such as twists and surface defects, significantly influence the running behavior of both high-speed and freight trains. These irregularities can induce dynamic forces that affect vehicle stability and performance[10]. The dynamic interaction between trains and tracks, including how bridges and track conditions impact vehicle behavior, has been extensively reviewed to understand these complexities[11-13]. Additionally, investigations into train dynamic derailment in railway turnouts caused by track failure provide insights into specific derailment scenarios and their prevention [14].

Advanced simulation techniques are crucial for analyzing the dynamic responses of rail vehicles under various track conditions. Multibody dynamics simulations are employed to evaluate factors like the curving performance of freight trains and the lateral forces on specialized train compositions[15,16]. Such simulations aid in predicting derailment scenarios and assessing the effectiveness of different safety measures[17,18]. For instance, dynamic simulations of derailments and their consequences provide critical insights into the underlying mechanisms.

This research specifically investigates the Wheel-Rail Interaction for a Shunter Locomotive on a Twisted Track. By analyzing the Nadal ratio (Y/Q) and wheel lift (Z-lifting), which are critical parameters for assessing wheel-rail stability, the research aim to gain insights into the safety margins under various operating conditions. This analysis will contribute to a deeper understanding of how twisted track conditions impact shunter locomotives and help in developing strategies to enhance safety and performance.

In the equation of the Nadal ratio (1), Y and Q to the lateral and vertical forces acting upon the rail and wheel, respectively. The angle δ is made when the wheel flange is in contact with the rail face, and μ is the coefficient of friction between the wheel and the rail. The Nadal ratio is a critical parameter in assessing the potential for derailment, with lower values indicating a safer interaction between the wheel and rail under various operating conditions[19].

$$\left(\frac{Y}{Q}\right) = \frac{\tan(\delta) - \mu}{1 + \mu \tan(\delta)} \tag{1}$$

METHODS

A simplified two-axle shunter locomotive model was developed for this study. The model incorporated essential components such as the car body and wheelsets, with corresponding mass and inertia properties. The suspension system was represented by linear springs and dampers acting between the car body and wheelsets. The parameters for these components, including mass, inertia, spring stiffness, and damping coefficients, are detailed in Table 1.

The model accounted for six degrees of freedom (DOF) for each axle, including longitudinal, lateral, and vertical displacements, as well as roll, pitch, and yaw motions. This comprehensive DOF analysis provided an accurate representation of the locomotive's dynamic behavior on a twisted track. The track geometry was defined by an H-profile with a 5% track twist, simulating critical conditions of a turning track.

Table 1. Locomotive parameters

Component	**Parameter**	**Value**	**Units**
Car Body	Weight	20400	kg
	Inertia (XX)	1012000	kg.m^2
	Inertia (YY)	5547800	kg.m^2
	Inertia (ZZ)	3200000	kg.m^2
Wheelset	Weight	1000	kg
	Inertia (XX, ZZ)	300	kg.m^2
	Inertia (YY)	70	kg.m^2
Suspension	Spring Stiffness (Vertical)	220000	N/m
	Spring Stiffness (Lateral)	150000	N/m
	Damping Coefficient	50000	N.s/m

The track geometry was defined by an H-profile with specified cross-sectional dimensions. A 5% track twist was introduced to simulate the critical conditions of a turning track. The macrogeometry parameters of the track, including L1, P11, S1, R1, P12, and dY1, were defined to characterize the track curvature on Table 2 and rail track can be seen on Figure 1.

Table 2. Rail track parameters

Parameter	**Value (m)**
L	10
P11	30
S1	150
R1	120
P12	30
dY1	0

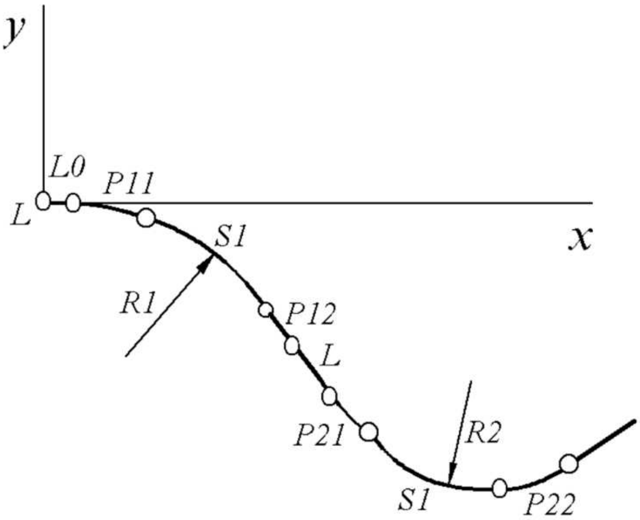

Figure 1. Rail track profile

A dynamic simulation was conducted using multibody dynamics software Universal Mechanism. The locomotive model was subjected to the defined track geometry, including the 5% track twist. The simulation parameters included vehicle speed, varying from 10 km/h to 20 km/h. Shunter locomotive model can be seen on Figure 2.

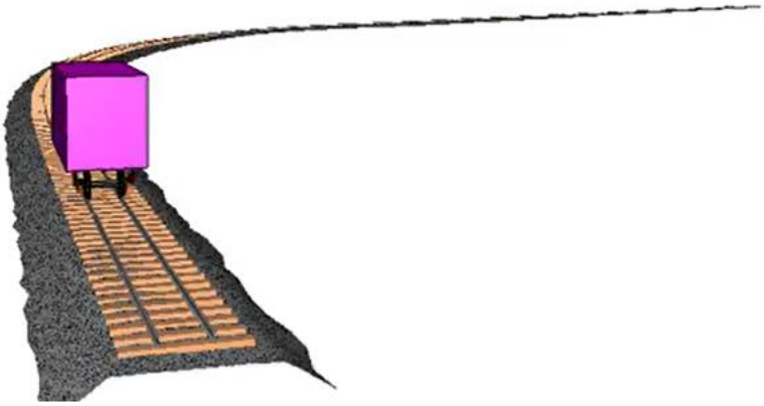

Figure 2. Shunter locomotive track

The boundaries of the simulation were carefully set to replicate real-world operating conditions. The track was assumed to be rigid, with no vertical or lateral movements, except those introduced by the twist. Additionally, the rail was assumed to be perfectly smooth, with no additional irregularities apart from the twist.

The wheel-rail contact was modeled using the Hertzian contact theory, which is appropriate for small contact areas like those between a wheel and rail. This model provided the basis for calculating the normal contact forces, while the Kalker's linear theory was used to estimate the tangential forces.

During the simulation, implicit Park method with computing Jacobians of stiff forces is used. Critical data were collected to analyze the interaction between the wheels and the rail. This data included the lateral and vertical forces acting on each wheel, which are essential for understanding the load distribution and potential for derailment. Additionally, the contact points between the wheel and rail were monitored to assess the stability and continuity of wheel-rail contact. Finally, the accelerations of both the wheelset and the car body were recorded to evaluate the dynamic behavior and overall stability of the locomotive. These comprehensive data points provided a detailed insight into the performance and safety of the train under various operating conditions.

The collected data were meticulously processed to calculate critical parameters essential for assessing wheel-rail interaction. The Nadal ratio (Y/Q), which represents the ratio of lateral force (Y) to vertical force (Q), was calculated for each wheel to evaluate the potential for derailment. The lateral (Y) and vertical (Q) forces at the wheel-rail interface were computed for each time step of the simulation. The Nadal ratio was then calculated as the ratio of these forces (Y/Q). This ratio was monitored to determine the likelihood of derailment, particularly when the ratio approaches or exceeds the critical value of 0.8.

The vertical displacement of the wheels was continuously tracked during the simulation to assess any lifting (Z-lifting) that might occur. Wheel lift was considered a critical safety parameter, as it indicates a potential loss of contact between the wheel and the rail, which could lead to derailment.

The calculated Nadal ratio and Z-lifting values were analyzed to assess the impact of track twist and speed on wheel-rail interaction. The results were compared to established safety criteria [20] ($Y/Q < 0.8$ and Z-lifting < 0.005m) to evaluate the safety margin. By following these steps, a comprehensive analysis of spring forces on train wheels under track twist conditions was conducted.

A key limitation of this study is the use of a simplified two-axle model, which may not fully capture the complexities of more extensive locomotive systems or multi-axle vehicles. The simplified suspension and wheel-rail interaction models exclude additional factors such as nonlinear suspension behaviors, wheel wear, and track elasticity, which could significantly affect the dynamics under real-world conditions. These limitations might result in underestimating or overestimating the actual forces experienced during operation, particularly in environments where multiple irregularities or more severe twists are present. Thus, the findings of this study should be interpreted with caution when applied to locomotives with more complex systems or operating under different conditions.

Additionally, while the model focuses on a single 5% track twist, it is important to recognize the potential influence of other track variations. Variations such as different twist percentages, track misalignments, and surface defects like corrugations could introduce additional forces that were not captured in this analysis. Future studies should consider a broader range of track irregularities, such as larger twists or combined defects, to provide a more comprehensive understanding of the dynamics involved. Incorporating these variables would enhance the model's predictive accuracy and offer a more complete assessment of the operational safety of shunter locomotives under varying conditions.

RESULT AND DISCUSSION

The analysis focused on determining the impact of track twist on the spring forces experienced by train wheels. The specific parameters investigated were the Nadal ratio (Y/Q) and wheel lift (Z-lifting) for a shunter locomotive traversing a track with a 5% twist at various speeds (10 km/h, 15 km/h, and 20 km/h). Nadal ratio can be seen on Figure 3.

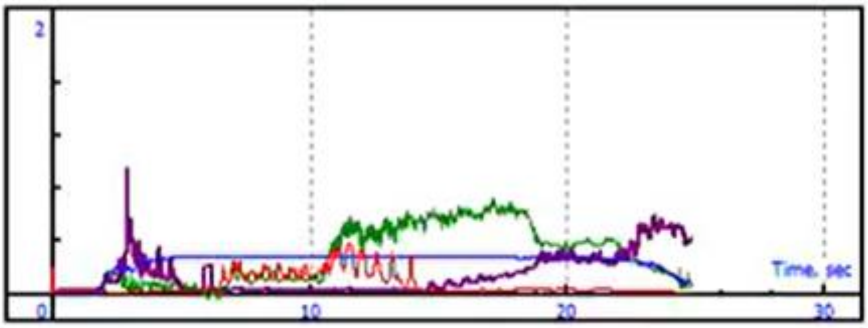

Figure 3. Nadal ratio of shunter locomotive

A positive correlation between vehicle speed and Nadal ratio was observed. As the speed increased, the lateral forces also increased, resulting in a higher Nadal ratio. However, even at the maximum speed, the ratio did not exceed the critical threshold, indicating safe operation under the simulated conditions.

The analysis of wheel lift (Z-lifting) across all simulations showed no instances of wheel lift, with the vertical displacement of the wheels remaining at zero as shown on Figure 4. This finding suggests that the vertical forces were sufficient to maintain continuous contact between the wheel and rail, thereby minimizing the risk of derailment due to wheel lift.

Despite the presence of a 5% track twist, which introduces vertical irregularities, the locomotive's suspension system effectively countered these irregularities, preventing any loss of contact. This demonstrates the robustness of the vehicle's design in handling such track conditions.

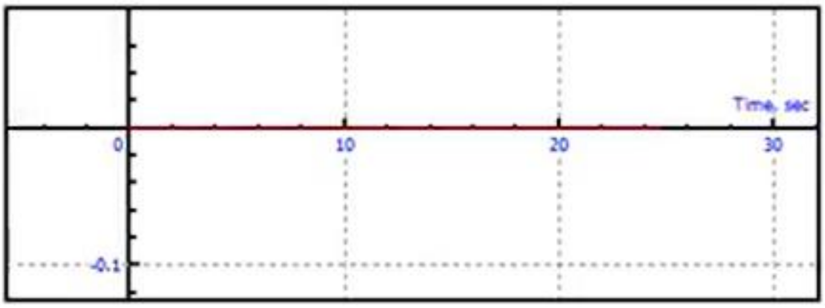

Figure 4. Z-Lifting of shunter locomotive

The results of this study align with previous research on wheel-rail interaction for rail vehicles, although most prior studies have focused on high-speed trains or freight vehicles rather than shunter locomotives. The observed Nadal ratios, all below 0.8, are consistent with established safety margins for rail operations, as highlighted by[20]. However, this study contributes uniquely by applying these analyses specifically to shunter locomotives on twisted tracks, a scenario less frequently explored in the literature.

The absence of wheel lift is also consistent with findings from[20], where robust suspension systems were found to mitigate the effects of track irregularities. However, unlike high-speed vehicles, shunter locomotives operate at lower speeds, which naturally reduces the likelihood of wheel lift. This study's results confirm that even under twisted track conditions, the risk remains negligible for the speed range tested.

The findings suggest that shunter locomotives, as modeled in this study, are unlikely to experience derailment due to excessive Nadal ratios or wheel lift when operating on tracks with up to a 5% twist. This has practical implications for railway operators, particularly in yards and industrial sites where shunter locomotives frequently operate on irregular tracks. The safety margins indicated by the Nadal ratio analysis provide confidence that these locomotives can handle moderate track twists without significant risk. However, the study also highlights the importance of regular track maintenance to ensure that twists remain within manageable limits. Any increase in track twist beyond the simulated 5% could potentially alter these safety margins.

While the simulation results provide valuable insights, they are subject to several limitations. The model assumes ideal track conditions, aside from the twist, without accounting for additional irregularities such as corrugations, wear, or varying stiffness along the track. Additionally, the simplified two-axle locomotive model does not capture the complexities of multi-axle vehicles, which may exhibit different dynamic behaviors.

The study focused on a single 5% track twist, but analyzing a wider range of track twists would provide a more comprehensive understanding of the locomotive's behavior under various track conditions. For instance, examining track twists greater than 5% could offer insight into the behavior under more extreme conditions where derailment risk may increase. Additionally, testing a broader range of speeds beyond 10-20 km/h could reveal how different operational speeds affect the Nadal ratio and wheel lift. By expanding the scope of the analysis to include more varied track conditions and speeds, a more thorough understanding of the locomotive's performance and the limits of its safe operation on irregular tracks can be gained.

A sensitivity analysis was conducted to assess the impact of varying key parameters—such as suspension stiffness, damping coefficients, and vehicle mass—on the Nadal ratio and wheel lift. Increases in suspension stiffness resulted in higher lateral forces, slightly raising the Nadal ratio. However, even in the stiffest suspension configurations, the Nadal ratio remained within safe limits. Reducing the damping coefficient led to more pronounced oscillations in lateral forces, but the Nadal ratio still remained below the critical threshold. Variations in vehicle mass had a more significant effect, with heavier loads increasing both lateral and vertical forces, thus slightly raising the Nadal ratio, though stability was maintained.

The sensitivity analysis also highlighted that vehicle speed had the most substantial impact on the Nadal ratio. As speed increased, the lateral forces grew, leading to higher Nadal ratios. However, even at the upper limit of 20 km/h, the Nadal ratio stayed within the safety margin, suggesting that moderate speed increases do not present an immediate risk under the tested conditions. These findings emphasize the importance of controlling key parameters, especially speed, load, and suspension settings, to minimize derailment risk, particularly on more severely twisted or irregular tracks.

Future research should focus on more comprehensive simulations that incorporate these additional factors. Field tests would also be beneficial to validate the simulation results and to assess the locomotive's performance under real-world conditions. Furthermore, extending the analysis to include different track twist percentages, speeds beyond 20 km/h, and more complex locomotive models could provide a deeper understanding of the wheel-rail interaction dynamics for shunter locomotives.

CONCLUSION

The analysis explored the dynamic behavior of a two-axle shunter locomotive on a twisted track using multibody dynamics simulations, with a focus on evaluating the Nadal ratio (Y/Q) and wheel lift (Z-lifting) to assess locomotive stability and safety. The results demonstrated that the maximum Nadal ratio, recorded at 0.707 under fully loaded conditions and at 20 km/h, remained well below the critical threshold of 0.8, indicating a low risk of derailment due to lateral forces. Additionally, no instances of wheel lift were observed, confirming that the locomotive design effectively counters the vertical irregularities introduced by a 5% track twist. These findings support the conclusion that shunter locomotives can operate safely on moderately twisted tracks at speeds up to 20 km/h, with a Factor of Safety for Nadal Ratio of 11.6%.

No instances of wheel lift were observed across all simulated conditions, suggesting that the vertical forces were sufficient to maintain continuous wheel-rail contact. This outcome confirms that the locomotive's design is effective in countering the vertical irregularities introduced by a 5% track twist. The study found a positive correlation between vehicle speed and Nadal ratio, as well as a slight increase in Nadal ratio with increased load. However, both remained within safe limits, further supporting the conclusion that the locomotive can operate safely on moderately twisted tracks at speeds up to 20 km/h. The results provide valuable insights into the safety margins of shunter locomotives operating on twisted tracks. By confirming that the Nadal ratio remains within safe limits and that wheel lift does not occur under the tested conditions, this study offers confidence in the stability and operational safety of shunter locomotives in environments where track irregularities are present.

Beyond ensuring safety, these findings carry important implications for locomotive design, track maintenance, and operational practices. From a design perspective, the results suggest that current suspension systems and configurations in shunter locomotives are adequate for handling moderate track irregularities. However, for future designs, consideration should be given to enhancing suspension systems to accommodate more extreme track twists or combined irregularities (e.g., undulations, surface defects) that could increase the risk of derailment.

In terms of track maintenance, the study emphasizes the importance of monitoring track twist levels and ensuring that track deformations remain within manageable limits (such as 5% twist). Regular inspection and maintenance practices can help prevent excessive track irregularities, which could challenge the safety margins observed in this study. Proactive track maintenance becomes especially crucial in industrial environments, where shunter locomotives frequently operate under less controlled conditions.

Operational practices also stand to benefit from these findings. Locomotive operators can optimize speed and load management to maintain safe operation even when track irregularities are present. The positive correlation between vehicle speed and Nadal ratio highlights the importance of speed control as a factor in minimizing derailment risks. Training programs that emphasize speed management and operational vigilance in environments with known track imperfections could further reduce derailment risks.

While the current study focused on a specific set of conditions, expanding the scope to include additional track geometries, speeds, and locomotive designs would provide a more comprehensive understanding of the dynamics involved. Future research should also consider real-world validation through field tests to confirm the results obtained from the simulations.

In conclusion, this study provides valuable insights into the operational safety of shunter locomotives on moderately twisted tracks, with implications for design improvements, track maintenance protocols, and operational best practices. These findings contribute to a deeper understanding of wheel-rail interactions and offer a basis for improving the overall safety and efficiency of shunter locomotive operations.

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