

ANALYSIS OF THE EFFECT OF DYNAMIC LOADS ON LRT JABODEBEK WHEEL FLANGE WEAR

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Abstract

Wheel wear is an important issue in the maintenance of rail-based transportation systems, particularly in the Jabodebek LRT system, which operates intensively in urban areas. This study aims to analyze the effect of dynamic loads on the rate of wear and to evaluate wheel life based on operational variations and track geometry. The research data includes primary data (interviews and wheel documentation) and secondary data (technical specifications, operational data, and track parameters) validated through triangulation. The analysis was conducted using a quantitative approach with dynamic load calculations referring to the Handbook of Railway Vehicle Dynamics and wear rates using Archard's Law corrected for geometric factors. The results show that the highest wear occurs on tracks with a curve radius < 125 m, which is predominantly triggered by lateral and centrifugal forces. Linear regression analysis shows a significant relationship between maximum dynamic load and daily wear rate ($R^2 = 99.7\%$). These findings confirm that wheel life on narrow curved tracks is shorter than on straight tracks. This research contributes to the development of academic studies in the field of railway engineering, particularly in wear modeling and dynamic load analysis in rail transportation systems. From a technical perspective, the results of this modeling can be applied as a basis for optimizing predictive maintenance schedules and wheel reprofiling intervals. Furthermore, these findings provide strategic recommendations for evaluating operational speed limits on tight curves to reduce lateral forces, which has direct implications for enhancing the service life efficiency of rolling stock assets and operational reliability.

Keywords: Dynamic load, lateral force, centrifugal force, wear, wheel disc

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INTRODUCTION

LRT Jabodebek is a driverless mass transportation mode utilizing a Communication Based Train Control (CBTC) system. While it effectively integrates urban agglomeration areas, increasing operational frequency and passenger volume have led to a high frequency of wheel component (keping roda) replacements. This rapid wear is primarily accelerated by specific track geometries, particularly tight curve radii, and continuous exposure to fluctuating dynamic loads.

These loads (comprising vertical, lateral, longitudinal, and centrifugal forces) continuously amplify wheel-rail contact stress [1]. Uncontrolled stress shortens service life, inflates maintenance costs, and poses operational safety risks. Previous studies confirm that

such load increases diminish material elasticity and accelerate fatigue in carbon steel wheels [2],[3]. Additionally, empirical measurements show that force factors fluctuate quadratically with train speed, peaking at critical track sections like sharp curves [4],[5]. Uncontrolled load fluctuations significantly reduce wheel service life, escalate maintenance costs, and introduce operational safety risks [6].

The LRT Jabodebek operates on elevated, ballastless Continuous Welded Rail (CWR). Complying with the Minister of Transportation Regulation No. 60 of 2012 and UIC 710R standards, the track layout includes numerous sharp curves with radii under 150 meters. These tight geometries generate extreme centrifugal forces, necessitating engineering compensations such as superelevation and gauge widening to mitigate severe flange-to-rail contact [7]. Locally, these conditions have been proven to trigger wheel diameter reduction, flange thinning, and hollow wear on wheel surfaces [8].

Despite extensive literature on material properties and generalized force modeling, a distinct research gap remains [9]. Few studies explicitly quantify wheel wear rates as a direct function of dynamic load calculations under the specific operational parameters and sharp-curve geometries unique to urban transit systems. Therefore, this study aims to bridge this gap by integrating dynamic load analysis with actual wear rates on the LRT Jabodebek system, providing a basis for optimizing predictive maintenance schedules.

RESEARCH METHODOLOGY

The method used in this research is quantitative with data collection stages where primary data was obtained from interviews with maintenance personnel and field observations. Secondary data includes passenger data, recent keping roda measurement results, technical specifications of LRT vehicles and rails, and curve rail condition data. The analysis stages are as follows:

Static Load Calculation

$$F_{static} = W / n \quad (1)$$

Where:

- F_{static} = Static wheel load
- W = Total weight of the rolling stock
- n = Number of wheels.

Dynamic Load Calculation

Dynamic loads are calculated using the following equation:

$$\Delta F_{dynamic\ max} = \Delta F_{static} + \Delta F_{track} + \Delta F_{speed} + \Delta F_{curve} \quad (2)$$

Where:

- $\Delta F_{dynamic\ max}$ = Maximum dynamic load increment.
- ΔF_{static} = Static load variation.
- ΔF_{track} = Load increment due to track conditions.
- ΔF_{speed} = Load increment due to speed.
- ΔF_{curve} = Load increment due to curving.

To integrate the influence of rail geometry, the Geometry Correction Factor (C_{geom}) is applied to ($F_{dynamic\ max}$). Thus, the adjusted maximum dynamic load ($F_{dynamic_max_adjusted}$) for wear calculation becomes:

$$\Delta F_{dynamic_max_adjusted} = \Delta F_{dynamic\ max} \times C_{geom} \quad (3)$$

Where:

$\Delta F_{dynamic_max_adjusted}$ = Adjusted maximum dynamic load increment.

$\Delta F_{dynamic\ max}$ = Maximum dynamic load increment

C_{geom} = Geometry correction factor.

Daily Wear Calculation

Using Archard's Law, daily wear (Δh) is calculated based on the relationship between dynamic load, material hardness, and daily travel distance [10]:

$$\Delta h = (k \times F_{dyn} \times s) / H \quad (4)$$

Where:

K = Wear coefficient influenced by lubrication

F_{dyn} = Dynamic force (N)

s = Sliding distance (m), equal to wheel travel distance

H = Material hardness (Pa)

Kejing roda Lifespan Calculation

Wheel lifespan (t) is analyzed by comparing the maximum allowable wear limit against the daily wear rate:

$$t = h_{max} / \Delta h_{daily} \quad (5)$$

Where:

h_{max} = Maximum allowable wear limit.

Δh_{daily} = Daily wear rate

Linear Regression Analysis

The linear regression method is used to analyze the relationship between dynamic load and kejing roda wear based on field data. The multivariate model is as follows:

$$\Delta h = \beta_0 + \beta_1 \times F_{dynamic\ max} + \varepsilon \quad (6)$$

Where:

β_0, β_1 = Regression coefficients;

ε = Error term

RESULTS AND DISCUSSION

Static Load Calculation (F_{static})

The total weight of the train consist in Newtons (N) is calculated by multiplying the mass in tons by gravitational acceleration (9.81 m/s²) and converting to Newtons. The static load per wheel is then obtained by dividing the total weight of the train consist by the number of wheels (48). Table 1 presents the results of static load calculations per wheel for various passenger load scenarios, ranging from empty to 100% full capacity.

The static load calculation shows significant load variation on each wheel, which directly depends on the number of passengers. The static load per wheel ranges from 40.727 kN (empty condition) to 58.791 kN (critical condition). Therefore, the static load used is 58.791 kN or critical. This static load serves as the fundamental component that will be the starting point for calculating other dynamic forces.

Table 1. Static Load Calculation per Wheel at Various Passenger Load Scenarios

Passenger Load Scenario	Total Weight (Ton)	Total Weight (N)	Number of Wheels (n)	Static Load per Wheel (N)	Static Load per Wheel (kN)
Empty	196.20	1,954,940.02	48	40,727.92	40.73
Normal	248.00	2,471,076.07	48	51,480.75	51.48
Full	267.60	2,624,259.40	48	54,672.07	54.67
Critical	287.80	2,821,961.60	48	58,790.87	58.79

Table 2. Load per Car Type

Car Type	Empty Weight (ton)	Passenger Capacity	Passenger Weight (ton)	Total Weight (Ton)	Static Load/Wheel (kN)
MC	33.50	206	14.42	47.92	58.76
M	32.30	224	15.68	47.98	58.84
T	32.30	224	15.69	47.98	58.84

From the calculation in Table 2, it was found that the static load per wheel varies between car types. The MC (Motor Car) has a static load per wheel of 58.76 kN. Cars M (Middle Car) and T (Trailer) have identical static loads per wheel of 58.84 kN, slightly higher than the MC due to their greater passenger weight (15.68 tons). Overall, this analysis indicates that the static load per wheel is not uniform across the entire train consist.

Dynamic Load Component Calculation ($\Delta F_{dynamic}$)

Calculations were performed considering additional load components due to static factors (ΔF_{static}), track irregularities (ΔF_{track}), speed effects (ΔF_{speed}), and curved track effects (ΔF_{curve}).

Table 3. Maximum Dynamic Load per Car

Car Type	ΔF_{static} (kN)	ΔF_{track} (kN)	ΔF_{speed} (kN)	ΔF_{curve} (kN)	F dynamic max (kN)
MC	58.74	15.44	34.60	9.13	117.97
M	58.82	15.44	34.67	9.15	118.05
T	58.82	15.44	34.67	9.15	118.05

The calculation results show that M and T type cars have the highest maximum dynamic load of 118.051 kN, derived from ΔF_{static} of 58.82 kN, ΔF_{track} of 15.44 kN, ΔF_{speed} of 34.67kN, and ΔF_{curve} of 9.15 kN. Meanwhile, the MC type car has a maximum dynamic load of 117.97 kN, slightly lower than M and T, resulting from ΔF_{static} of 58.74 kN, ΔF_{track} of 15.44 kN, ΔF_{speed} of 34.60 kN, and ΔF_{curve} of 9.13 kN.

In general, the difference in $F_{dynamic_max}$ values between car types is primarily influenced by static load variations, while the influence of track irregularity, speed, and curvature components is relatively similar for M and T types.

Geometry Correction Factor Calculation (C_{geom})

Of the total 90 curve points evaluated, rail geometry conditions varied significantly. A large number of curve points showed superelevation and/or gauge widening deviations outside permissible tolerance limits (UIC 710R). This condition causes increased C_{geom} values at most points, indicating potential increased wheel wear due to non-optimal rail geometry. The distribution of rail geometry conditions is as follows: 1 curve point shows both parameters (P_{actual} or G_{actual}) within tolerance, resulting in $C_{geom} = 1$; 87 curve points have one or both geometry parameters outside tolerance, resulting in $C_{geom} = 2$; and 2 curve points show both geometry parameters (superelevation and widening) outside tolerance, resulting in $C_{geom} = 3$.

This indicates that most curves on the LRT Jabodebek route have non-compliant rail geometry conditions, which will significantly increase wheel wear. The C_{geom} factor will be used to adjust dynamic loads and effective sliding distance in daily wear calculations.

Daily Wear Calculation

Based on LRT Jabodebek's operational schedule, there are 184 one-way trips per day, equivalent to:

$$184 / 2 = 92 \text{ Round Trips}$$

The route covered in one round trip on the Bekasi Line is Dukuh Atas Station - Jati Mulya - Dukuh Atas with a one-way track length of 27.3 km, thus:

$$\text{Round Trip Distance} = 27.3 \times 2 = 54.6 \text{ km}$$

With a total of 92 round trips per day, the total daily travel distance for all trainsets is:

$$92 \times 54.6 = 5,023.2 \text{ km/day}$$

If operational data from PT KAI LRT Jabodebek indicates 11 active trainsets during weekdays (Monday-Friday) and 10 trainsets on weekends (Saturday-Sunday), assuming weekday operations, from the total daily travel distance of 5,023.2 km divided by 11 trainsets, the average distance per trainset per day (weekday) is:

$$5,032.2 / 11 = 456.63 \text{ km/trainset/day}$$

For the proportion of daily travel distance on curved and straight segments, the total one-way track length from Jatimulya-Cawang-Dukuh Atas is 27.3 km. The total curved segment length in one direction is approximately 9 km, thus the total straight segment length in one direction is approximately 18.3 km. For a daily travel of 456 km/day:

$$\text{Total daily curved km} = (456 \text{ km/day}) \times (9 \text{ km} / 27.3) = 150.33 \text{ km/day}$$

$$\text{Total daily straight km} = (456 \text{ km/day}) \times (18.3 \text{ km} / 27.3) = 305.67 \text{ km/day}$$

From the calculations performed, the total average daily wear calculation can be completed as follows:

- Average wear per kilometer for curved segments

$$\text{Maximum dynamic force} = 151.992 \text{ N}$$

$$\text{Wear per meter of curved track} = 3.20912 \times 10^{-6}$$

- Average wear per kilometer for straight segments

$$\text{Total straight segment force} = 108,886.44 \text{ N}$$

$$\text{Straight segment wear} = 4.67376 \times 10^{-6} \text{ m/km}$$

- Combined total average daily wear = 1.7287×10^{-8} m/km

Wheel Lifespan Calculation Results

To estimate wheel lifespan, a maximum wear threshold of 5 mm (0.005 m) is used. The calculation is performed in two stages: based on maximum travel distance and converted to operational time.

- Maximum travel distance = 189,235 km
- Operational time calculation:
 Days = 634 days
 Months = 21.13 months
 Years = 1.76 years

Table 4. Wheel Lifespan Calculation per Car Type

Car Type	ΔF static (kN)	Passenger Capacity	Total Weight/Car (kN)	F dynamic max (kN)	Wheel Lifespan (km)
MC	58.74	206	469.93	117.97	289,25
M	58.84	224	470.52	118.05	288,88
T	58.84	224	470.52	118.05	288,88

Overall, these results indicate that differences in wheel lifespan between car types are primarily influenced by variations in static and maximum dynamic loads. All three car types have relatively similar values without significant differences.

Based on international standards and technical studies related to Light Rail Transit operations, wheel tread wear tolerance limits generally range from 5-8 mm; for LRT Jabodebek specifically, 5-8 mm for Motor Car (MC) wheels and 5-6 mm for Trailer Car (T) wheels. In this research, a conservative (approximation) value of $h_{max} = 5$ mm is used as the maximum wheel tread wear limit, referring to common safe usage tolerance limits often used as wheel re-profiling references depending on wheel type and operational load.

According to technical reports, the minimum allowable flange wear for LRT Jabodebek wheels is 8 mm. The wheel flange is the side part of the wheel most at risk of wear on curves, and this is relevant as a maximum wear reference for LRT wheel tread or flange [11].

Linear Regression Analysis Results Interpretation

To analyze the relationship between Maximum Dynamic Load (F_{dyn_max}) and Daily Wheel Wear Rate (Δh), linear regression analysis was employed. This analysis was conducted using SPSS software based on previously calculated wear data. The results are shown in Table 5:

Table 5. Regression Statistics

Regression Statistics	Value
Multiple R	0.998870719
R Square	0.997742714
Adjusted R Square	0.997717063

Standard Error	0.000073200
Observations	90

Based on Table 5, the following conclusions can be drawn:

- Multiple R Value (Correlation Coefficient): 0.998
The value of 0.998 indicates a very strong and positive correlation between dynamic load and daily wear. This means that as dynamic load increases, daily wheel wear also tends to increase.
- R Square (Coefficient of Determination): 0.997
This indicates that 99.7% of daily wear variation can be explained by maximum dynamic load, track geometry, and track condition corrections; the remaining 0.3% is caused by other factors such as wheel condition, material properties, or lubrication.
- Adjusted R Square: 0.997
The high value indicates the model remains stable and robust despite the large data volume.
- Standard Error
The very small standard error value indicates that model predictions are quite accurate and close to actual values.
- Observations: 90 curve points

CONCLUSION

Based on the comprehensive analysis of dynamic loads and track geometry on the LRT Jabodebek system, the following conclusions are established regarding the wheel degradation process, maintenance strategies, and operational policies. Dynamic load components (specifically vertical, lateral, longitudinal, and centrifugal forces) simultaneously accelerate the continuous wear of wheel components. Among these variables, the centrifugal and lateral forces generated on curved alignments act as the dominant factors driving the excessive wheel wear rate. The combined interaction of these extreme forces induces severe contact stress and extreme flange-to-rail friction. Consequently, observational data confirms that the highest daily wear rates directly correlate with track segments featuring tight curve radii, particularly those under 125 meters. These specific geometric constraints dictate the physical limits of the system, drastically shortening the operational lifespan of the wheels when compared to steady-state operations on straight track alignments.

Simple linear regression analysis mathematically validates this material degradation model. The maximum dynamic load functions as a highly accurate predictor of the daily wheel wear rate, evidenced by an exceptional coefficient of determination (R^2) of 0.997. This near-perfect quantitative correlation affirms that while fluctuating dynamic loads serve as the direct mechanical catalyst for material loss, the overarching track geometry ultimately dictates the magnitude and severity of these loads. Therefore, the architectural layout of the track is the fundamental determinant in the accelerated degradation process, proving that wheel wear in this specific urban transit network is highly predictable based on spatial route characteristics.

From a practical engineering perspective, these findings provide a critical, data-driven foundation for optimizing rolling stock maintenance strategies. The established wear-rate model enables railway operators to transition from traditional, reactive component

replacements to advanced predictive maintenance regimens. By utilizing the proven dynamic load correlations, train depots can mathematically project the remaining wheel lifespan with high precision. This capability allows for the strategic optimization of wheel reprofiling intervals tailored to the specific, curve-dominated routes traversed by each trainset. Ultimately, this proactive approach significantly enhances fleet availability and effectively controls lifecycle costs (LCC) by preventing premature wheel condemnation.

To mitigate the rapid deterioration of rolling stock assets, comprehensive operational policies must be implemented synergistically between infrastructure and rolling stock divisions. It is highly recommended that management evaluates and enforces stricter operational speed restrictions, specifically tailored for tight curves, to directly diminish destructive lateral forces. Furthermore, track maintenance policies should integrate enhanced rail lubrication systems and regular gauge widening evaluations on sharp curves to minimize flange friction. Academically, this study enriches the field of railway engineering by explicitly bridging dynamic load calculations with empirical wheel wear rates in a driverless urban transit context, fostering a deeper understanding of wheel-rail interface management for enhanced operational reliability.

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