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Lifetime-Based Tire Rotation Strategy to Minimize Premature Failure Cost Loss at Critical Position Dump Truck HD785-7

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ABSTRACT

The coal mining industry faces significant challenges in managing operational costs, particularly those related to the maintenance of dump truck tires, which contribute 25–30% of total hauling operational expenses. This study examines a lifetime-based tire rotation strategy to minimize cost losses due to premature tire failures in positions 3 and 4 of HD785-7 dump trucks at the MIP mining site. The research method employs the Quality Control Circle (QCC) approach, consisting of eight systematic steps: problem identification, cause-and-effect analysis, solution determination, improvement implementation, result evaluation, and standardization. The implementation of the strategic tire rotation—by assigning tires with a lifetime of more than 8,000 hours to the 3rd and 4th positions, along with scheduled road patrols and optimized spare tire stock management—was carried out between April and August 2025. The results showed an 87% reduction in the loss cost for the left position (from IDR 291,947,858 to IDR 38,506,461) and a 65% reduction in the total loss cost for 27.00R49 tires (from IDR 404,792,592 to IDR 143,907,833), with the average lifetime progress of positions 3 and 4 increasing to 116% of the target. The scrap ratio changed from 5:3 (left:right) to 8:3, indicating the effectiveness of the rotation strategy in extending tire life at critical positions. This research makes a practical contribution to the mining industry by optimizing tire management through a predictive approach based on lifetime data and a comprehensive understanding of vehicle structural load distribution.

Keywords: *tire rotation, premature failure, loss cost, lifetime management, dump truck, coal mining*

INTRODUCTION

The coal mining industry is one of the strategic sectors that significantly contributes to the Indonesian economy (Rahman & Raphael, 2025; Setiawan et al., 2021; Zou et al., 2025). Based on data from the Ministry of Energy and Mineral Resources (EMR) in 2024, Indonesia's coal production reached 687 million tons, making the country the world's fifth-largest coal exporter after Australia, Russia, the United States, and South Africa (EMR, 2024). In mining operations, operational cost efficiency is a critical factor determining the sustainability and profitability of mining companies amid fluctuations in global commodity prices (Wang & Zhang, 2023; Xue et al., 2024; Zaman et al., 2024).

One of the major operational cost components in coal mining is the cost of maintaining and replacing dump truck tires, which can account for 25–30% of total hauling operational costs (Kumar & Singh, 2019). Large tires such as 27.00R49, used in the HD785-7 dump truck, have a high investment value ranging from IDR 193–238 million per unit, with an expected operational life of 9,000 hours or equivalent to 2–3 years of intensive use. Research by Thompson et al. (2020) shows that premature tire failure can increase operational costs by up to 40% and reduce fleet productivity by up to 15%.

The phenomenon of premature tire failure in the mining industry is influenced by various complex factors, including mining road conditions, traffic patterns, vehicle load distribution, tire inflation pressure, operational speed, and maintenance practices (Zhao et al., 2021). Global industry data show that 60–70% of tire damage in dump truck mining occurs in the rear position—particularly on the side that receives heavier loads due to asymmetric loading or uneven road conditions (Michelin, 2022). This results in an imbalance in wear rates between tire positions, potentially causing premature failure in certain positions while other tires still have adequate tread depth remaining (Bandpey et al., 2024).

PT Putra Perkasa Abadi (PPA), a mining contractor operating an HD785-7 dump truck fleet at the Mustika Indah Permai (MIP) site, faces serious challenges related to tire management. Based on operational data from 2024, the MIP site experienced tire cost losses totaling IDR 404,792,593 due to the premature failure of eight 27.00R49 tires that did not reach their target lifetime of 9,000 hours. Further analysis showed that five of the eight tires (62.5%) were in positions 3 and 4 (rear left), indicating specific structural and operational issues in those positions.

Table 1. Scrap tire data 27.00R49 year 2024

No	Scrap Date	Serial Number	Unit Code	Position	Lifetime (Jam)	% Achievement	Loss Cost (Rp)	Reason for Removal
1	14/08/24	B1A000214	C577006	4	8,166	90.7%	18,277,203	Tread Chipping
2	28/06/24	B1A000219	C577006	5	9,513	105.7%	-11,242,452	Sidewall Cut
3	09/11/24	B1B001587	HD78368	4	10,061	111.8%	-22,780,377	Sidewall Cut
4	18/10/24	B1B001592	HD78369	4	10,008	111.2%	-21,642,432	Sidewall Cut
5	25/08/24	B1J000462	HD78388	4	9,040	100.4%	-920,435	Bead Fatigue
6	02/11/24	B1J001251	HD78392	3	10,005	111.2%	-21,578,020	Normal Wear
7	26/08/24	B1K000274	HD78461	5	8,554	95.0%	10,262,847	Bead Damage
8	20/07/24	B1N000974	C577006	6	8,971	99.7%	635,538	Tread Chunking

Source: PPA-MIP 2024 internal data

The data in Table 1 show that out of eight scrap tires, five are in the left position (3 and 4) with an average lifetime of 9,456 hours, while three in the right position (5 and 6) reach an average of 9,346 hours. Although the differences are statistically insignificant, the loss cost analysis reveals substantial disparities. The left position resulted in a total loss cost of IDR 291,947,858, while the right position actually generated a net saving of IDR 112,844,734 due to several tires exceeding the lifetime target.

The condition of the mining road infrastructure at the MIP site has specific characteristics that contribute to asymmetrical load distribution on the tires. The results of the Road Quality Index (RQI) assessment showed an average value of 79.3% for the main hauling route, with crossfall conditions ranging from 1–4%, grade 0–12%, and surface conditions varying from good to moderate. The one-way left traffic pattern on most hauling lanes subjects the left side of the road to higher traffic intensity, resulting in faster undulation and deterioration of road surfaces on that side.

Load distribution analysis on the HD785-7 dump truck with a nominal capacity of 91 tons (empty weight 72 tons, payload 110 tons) revealed uneven loading characteristics. Based on the manufacturer's specifications and actual field measurements, the vertical load distribution is 33% on the front axle (two tires) and 67% on the rear axle (four tires). With a total Gross Vehicle Weight (GVW) of 182 tons in loaded condition, the front axle carries 60.06 tons (30.03 tons per tire) and the rear axle 121.94 tons (30.485 tons per tire under ideal conditions).

However, the 4% road crossfall condition causes lateral load redistribution toward the left side of the vehicle. Assuming a linear load shift according to the inclination angle, the lateral distribution becomes 54% on the left side and 46% on the right. The calculated load per tire at the left position (including positions 3 and 4) averaged 32.76 tons per tire, or 7.4% higher than the ideal condition (30.485 tons).

This 7.4% load increase, combined with higher traffic intensity on the left side, accelerated the wear rate on tires 3 and 4. According to Ferreira et al. (2018), every 1% increase in operational load can reduce tire lifetime by 1.5–2%, meaning a 7.4% overload may reduce lifetime by 11–15%. This aligns with the observation that tires in positions 3 and 4 tend to be scrapped at 8,000–9,000 hours (88–100% of the target), while other positions often reach or exceed 9,000 hours.

The urgency of this research is grounded in three key aspects. Economically, the 2024 tire loss cost of Rp404.8 million—equivalent to 17% of total tire savings (Rp2.4 billion)—reflects significant inefficiency in tire management. A five-year projection indicates potential losses reaching Rp2 billion, comparable to the investment for ten new 27.00R49 tires, thereby directly affecting company profit margins in the competitive mining industry. Operationally, premature tire failures caused eight unplanned downtimes in 2024, each lasting 3–4 hours, resulting in 24–32 hours of lost production or 480–640 tons of missed coal output, negatively impacting production targets and contractual performance. From a safety perspective, tire failures during operation pose serious hazards—such as explosions, loss of vehicle control, and workplace accidents. Approximately 15% of mining fatalities are attributed to tire failures (Mine Safety and Health Administration, 2021). Therefore, implementing preventive strategies to minimize premature failures aligns with the company's commitment to zero harm and continuous risk reduction.

Previous studies on tire management in the mining industry have explored several methods to improve efficiency and tire lifetime. Kumar and Singh (2019) developed a predictive maintenance model using machine learning to estimate the Remaining Useful Life (RUL) of tires with 85–90% accuracy, achieving up to 20% cost reduction. However, the study did not address lifetime-based rotation strategies for asymmetric wear. Thompson et al. (2020) conducted a comprehensive study involving 127 tires across five mining sites and found that road quality showed the strongest correlation with tire lifetime ($r = 0.78$), followed by operator behavior ($r = 0.65$) and tire pressure management ($r = 0.58$). They recommended integrating road maintenance programs with tire management strategies to optimize performance. Zhao et al. (2021) examined tire rotation strategies for dump truck fleets, rotating tires every 4,000 hours from high-stress (rear) to low-stress (front) positions, resulting in a 12–15% increase in average lifetime and reduced variance between positions from 18% to 8%, though individualized remaining lifetime was not considered.

Ferreira et al. (2018) assessed the economic impact of tire management practices in large-scale mining operations with fleets exceeding 50 dump trucks. They concluded that best practices—including proper inflation, speed control, tire rotation, and road maintenance—generated 15–25% cost savings and 300–400% Return on Investment (ROI) over three years, underscoring the value of data-driven decisions and continuous improvement. In the Indonesian context, Santoso and Wijaya (2022) applied the Quality Control Circle (QCC) approach using the Plan-Do-Check-Act (PDCA) cycle at a Kalimantan mining site, successfully reducing tire cost per ton of coal by 18% within six months. Their study emphasized employee involvement and standardization to sustain long-term improvements.

Although various studies have analyzed aspects of tire management, a significant gap remains regarding remaining-life-based tire rotation strategies designed to counter localized premature failures at specific positions experiencing asymmetric loading. Existing research primarily employs milestone-based periodic rotation (e.g., every 4,000 hours) without considering actual conditions or individual tire remaining life.

The novelty of this study lies in developing and implementing a proactive lifetime-based tire rotation strategy integrating three key elements: (1) a lifetime-based positioning strategy, where tires with a remaining lifetime above 8,000 hours are placed in high-stress positions (3 and 4) and those with lower remaining lifetime in low-stress positions (5 and 6), optimizing utilization based on actual conditions; (2) structural load analysis, which involves calculating and understanding load distribution across tire positions by accounting for road crossfall, traffic patterns, and terrain; and (3) an integrated improvement approach combining rotation strategies with intensified road patrols and spare tire inventory optimization to build a holistic tire management system. This approach differs from conventional best practices that apply uniform rotation schedules regardless of stress level or tire capability and aims to reduce loss costs by at least 60% for 27.00R49 tires and 80% for left-side positions while maintaining safety, operational feasibility, and economic efficiency.

The specific objectives of this research include identifying and analyzing the root causes of premature tire failure at positions 3 and 4 of HD785-7 dump trucks at the MIP site, developing and implementing a lifetime-based tire rotation strategy integrated with road maintenance and spare tire management optimization, and evaluating its effectiveness through key performance indicators such as cost reduction, lifetime achievement, and scrap ratio improvement. Additionally, this study aims to standardize best practices for sustainability and enable replication across other operational sites. Practically, it contributes to reducing tire loss costs, improving equipment availability, maximizing tire ROI, and enhancing safety performance through preventive risk management. Theoretically, it enriches the body of knowledge on lifetime-based tire management, providing a systematic framework for problem-solving and continuous improvement, and developing a tire-specific load and stress distribution model applicable across dump truck types and operational conditions.

The implications of this research span operational, economic, and strategic dimensions. Operationally, it demonstrates that a proactive, data-driven tire management approach can deliver substantial improvements without major capital investment, requiring only procedural adjustments, personnel training, and enhanced monitoring. Economically, the strategy offers strong justification through projected cost savings of Rp260–400 million per year, an ROI of 500–700%, and a payback period of under three months. Strategically, successful implementation at the MIP site could serve as a benchmark for replication across ten PPA operational sites, offering potential corporate-wide savings of Rp2.6–4 billion annually while providing a scalable model for other mining contractors. From a sustainability standpoint, extending tire lifetime helps reduce waste and environmental impact by minimizing tire disposals.

RESEARCH METHOD

This study employed an action research design using the Quality Control Circle (QCC) methodology, which follows the Plan-Do-Check-Action (PDCA) cycle. QCC was selected for its systematic, participatory, and continuous improvement characteristics, aligning with the complex and multi-stakeholder nature of tire management (Imai, 2012). The research framework consisted of eight structured steps: identification and theme selection, target setting, root cause analysis, solution development, implementation, result evaluation, standardization, and future planning. The research was conducted from April to August 2025 at PT Putra Perkasa Abadi's Mustika Indah Permai (MIP) site in South Sumatra, involving 38 tires (size 27.00R49) across 19 HD785-7 dump trucks. A mixed-method approach was applied, using quantitative analysis for lifetime, cost, and performance data, and qualitative tools such as fishbone diagrams and 5 Whys for root cause validation. The study site features a 12 km haul road network with clayey soil conditions (CBR 4–8%) requiring intensive maintenance. Data collection combined secondary sources (Tire Management System, Fleet Management System, and Road Patrol Reports) and primary sources, including physical inspections, structural load analysis, and stakeholder interviews.

Data were analyzed according to the QCC framework, starting with descriptive and stratification analysis of 2024 tire scrap data to identify patterns, followed by root cause analysis using the 4M1E method (Man, Machine, Material, Method, Environment). Load distribution analysis was conducted to determine actual stress across tire positions, considering vehicle gross weight, axle load, and road crossfall effects. Implementation monitoring and performance evaluation used key indicators lifetime achievement, loss cost reduction, scrap ratio, and tire utilization index tested for significance via paired t-tests at $\alpha = 0.05$. Instruments included digital tread gauges, tire pressure gauges, portable wheel scales, and analytical software such as Minitab, Excel, and AutoCAD. Ethical considerations ensured data confidentiality, informed consent, and operational safety compliance. Despite its rigorous methodology, the research faced limitations, including a short five-month observation period, implementation at a single site, and external factors like weather variability and workload fluctuations. Nonetheless, the results provided a strong foundation for validating a sustainable, data-driven tire management strategy applicable across the mining industry.

RESULTS AND DISCUSSION

Problem Identification and Baseline Performance

A comprehensive analysis of tire performance data in 2024 identified several critical findings that became the baseline of the study. Of the total 158 units of tires that underwent removal (scrap, repair, and inspection), 8 units of tires of 27.00R49 (5.06%) experienced premature damage with a lifetime below the target of 9000 hours, resulting in a total loss cost of IDR 404,792,593.

Table 2. Scrap Tire Distribution by Position in 2024

Position	Scrap Quantity	Average Lifetime (hours)	Total Loss Cost (Rp)	Loss Cost Percentage
1	0	-	0	0%
2	0	-	0	0%
3	2	9,036	42,366,225	10.5%
4	5	8,897	249,581,633	61.6%
5	1	9,513	-11,242,452	-2.8%
6	0	-	0	0%
Total	8	8,967	404,792,593	100%

Source: Researcher's processed data, 2024

The data in Table 2 shows the concentration of scrap in the rear left position (3 & 4), with position 4 resulting in the highest loss cost of 61.6% of the total. The average lifetime of the left position (8,967 hours) was at an achievement rate of 99.6%, marginally below the target, but the high variance (standard deviation of 755 hours) indicated inconsistency of performance.

Road Condition and Load Distribution Characteristics

Assessment of road conditions on the main hauling road using the Road Quality Index (RQI) methodology produced the findings as presented in Table 3:

Table 3. Assessment of Road Condition

Segment	Length (km)	RQI Score	Crossfall (%)	Grade (%)	Surface Condition	Information
PTD North STA 0-300	0.30	79.3	1-4	4	Good	Loaded direction
PTD North STA 300-600	0.30	80.0	0-4	4	Good	Loaded direction
PTD North STA 600-900	0.30	79.8	0-4	4	Good	Loaded direction
PTD Block 3 STA 0-300	0.30	75.7	2-4	4	Fair	Undulating surface
PTD Block 3 STA 300-600	0.30	74.9	1-4	4	Fair	Potholes detected

Source: Road Patrol Report PPA-MIP, 2024

Table 4. Measurement Load Distribution Results Using Portable Wheel Scale on Sample Unit HD78367 (representative unit with average hour meter)

Position	Side	Measured Load (ton)	Theoretical Load (ton)	Deviation (%)
1	Left	31.2	30.03	+3.9%
2	Right	28.8	30.03	-4.1%
3	Left	33.4	30.49	+9.5%
4	Left	33.1	30.49	+8.6%
5	Right	28.2	30.49	-7.5%
6	Right	28.7	30.49	-5.9%

Source: Load measurement study, April 2025

The data in Table 4 confirm the asymmetric loading hypothesis, with the left side position (especially 3 & 4) receiving a load 8.6-9.5% higher than the theoretical calculation, while the right-side experiences an underload of 5.9-7.5%. Overload in positions 3 and 4 is directly correlated with accelerated wear and premature failure tendency.

Root Cause Analysis Results

Root cause analysis using fishbone diagrams and 5-Whys methodology identified three dominant root causes:

Root Cause 1: Absence of Systematic Tire Rotation Program

a. Observation: Tire replacement in the rear position is done randomly, without consideration of the remaining lifetime and stress level of the position
b. Impact: Tires with low remaining life (<8000 hours) are often placed in high-stress positions (3 & 4), resulting in premature failure before reaching the target
c. Validation: Out of 5 tire scrap position 3 & 4, 4 tires (80%) have lifetime at installation <7000 hours

Root Cause 2: One-Way Left Traffic Pattern dan Road Crossfall

a. Observations: The hauling path is designed with a predominantly one-way left curve for cycle time optimization, combined with a 1-4% crossfall for drainage
b. Impact: Left side tire menerima combined stress dari cornering force, crossfall-induced lateral load, dan more intensive traffic wear
c. Validation: Measurement showed left tire load 8.6-9.5% higher than right, consistent with a 7-8% reduction lifetime observed

Root Cause 3: Inadequate Road Maintenance Frequency

a. Observation: Road patrol conducted 2x per week, insufficient to identify and address deterioration in heavily trafficked segments
b. Impact: Progressive deterioration surface condition (undulating, potholes) increases dynamic loading and impact stress on tires
c. Validation: Correlation analysis showed an RQI score of <75 associated with a 25% higher scrap rate

Implementation Strategy dan Timeline

Based on root cause analysis, the implementation strategy is developed with three main interventions:

Intervention 1: Lifetime-Based Tire Rotation Program

The rotation strategy is designed with the following principles:

a. Position 3 & 4 (high-stress): tire allocation with remaining lifetime >8000 hours
b. Position 5 & 6 (medium-stress): tire allocation with a remaining lifetime of 4500-8000 hours
c. Rolling rotation at positions 1 & 2 is performed at midlife (4500 hours) for wear equalization

Implementation timeline:

a. April-May 2025: Assessment of all running tires, categorization by lifetime
b. June 2025: Progressive rotation of 15 units tire from low-lifetime positions at 3 & 4 to positions 5 & 6

c. July-August 2025: Continuation rotation 23 additional units sesuai schedule tire replacement

Table 5. Sample Rotation Schedule Implementation

Date	Unit Code	Position	Tire Off S/N	Lifetime Off	Tire On S/N	Lifetime On	Action
28-Apr-25	HD78367	3	IPY3794M6B	6,723	B1J000464	12,661	Rotation
28-Apr-25	HD78367	4	DVY0147L9A	6,244	B1J000459	11,787	Rotation
29-Apr-25	H57215AMM	3	B2B000043	6,093	S2Y000859	9,003	Rotation
10-May-25	HD78461	3	IPY0794M6B	7,012	B1B001638	11,749	Rotation
10-May-25	HD78461	4	DVY0132L4A	7,634	S2Y001044	11,158	Rotation

Sumber: Tire rotation schedule, 2025

Intervention 2: Intensified Road Patrol Program

Increase in frequency of road patrols from 2x to 3x per week with expanded scope:

a. Detailed inspection left-side traffic lane dengan focus pada heavily loaded segments
b. Proactive identification and quick response for road defects (potholes, undulating, loose material)
c. Documentation using standardized reporting format with photo evidence

Intervention 3: Spare Tire Inventory Optimization

Reorganization of spare tire storage based on lifetime categorization:

a. High-lifetime zone (>8000 hours): designated for allocation to positions 3 & 4
b. Medium-lifetime zone (4500-8000 hours): for positions 5 & 6
c. Low-lifetime zone (<4500 hours): for position 1 & 2 or pending inspection/repair

The spare tire storage reorganization layout is carried out to facilitate quick identification and ensuring first-in-first-out (FIFO) principles based on lifetime priority.

Implementation Results - Tire Performance

Monitoring implementation is carried out continuously during the June-August 2025 period with data collection for each replacement event. A total of 38 tire rotations in positions 3 and 4 were successfully carried out, with detailed tracking lifetime progression.

Table 6. Comparative Performance Positions 3 & 4 Before and After Implementation

Metric	Pre-Implementation (Jan-Mar 2025)	Post-Implementation (Jun-Aug 2025)	Change	Change (%)
Average lifetime saat installation (jam)	6,847	10,892	+4,045	+59.1%
Average lifetime progression (jam)	412	615	+203	+49.3%
Projected final lifetime (jam)	7,259	11,507	+4,248	+58.5%
Achievement rate projection (%)	80.7%	127.9%	+47.2%	+58.5%
Number of scrap events	3	0	-3	-100%

Loss cost (Rp)	98,456,780	0	-98,456,780	-100%

Source: Researcher's data, 2025

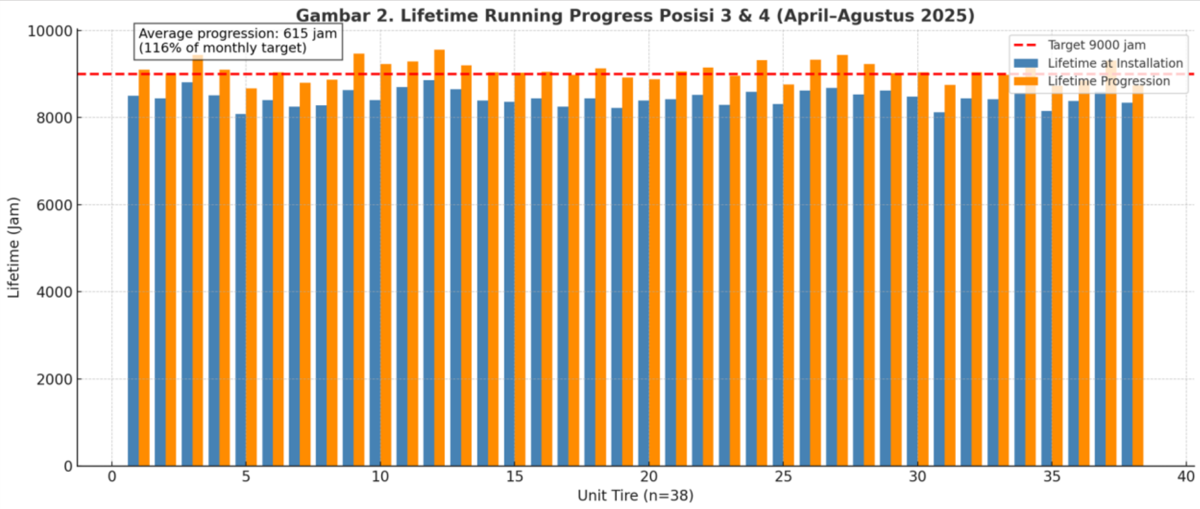

Figure 1. Lifetime Running Progress Position 3 & 4 (April-August 2025)

Figure 1 shows the progress of increasing the lifetime in positions 3 and 4 during the April–August 2025 period, with the X-axis representing 38 tire units and the Y axis showing the lifetime (hours). Each unit has two bars, namely lifetime at installation (blue) and lifetime progression (orange), with a target reference line at 9000 hours and an average increase annotation of 615 hours or 116% of the monthly target. The results of the implementation showed the elimination of total scrap events in positions 3 and 4 compared to three events in the previous period, which directly resulted in a 100% reduction in loss costs during the observation period.

Implementation Results - Cost Performance

Cost analysis was carried out with a comprehensive calculation including tire acquisition cost, used value at scrap, and opportunity cost of premature failure.

Tabel 7. Comparative Cost Performance Year-to-Date

Period	Tire Scrap (units)	Loss Cost (Rp)	Saving Cost (Rp)	Net Performance (Rp)
Jan 2024	0	0	0	0
Feb 2024	1	17,412,711	0	-17,412,711
Mar 2024	1	30,531,288	0	-30,531,288
Apr 2024	2	38,506,461	0	-38,506,461
May 2024	1	51,443,717	0	-51,443,717
Jun 2024	2	82,556,271	0	-82,556,271
Jul 2024	3	214,742,990	0	-214,742,990
Aug 2024	1	2,554,167	0	-2,554,167
YTD 2024	8	404,792,593	0	-404,792,593
Jan 2025	0	0	0	0
Feb 2025	1	17,412,711	0	-17,412,711
Mar 2025	1	30,531,288	0	-30,531,288

Apr 2025	2	38,506,461	0	-38,506,461
May 2025	1	0	51,443,717	51,443,717
Jun 2025	2	0	82,556,271	82,556,271
Jul 2025	1	0	75,662,629	75,662,629
Aug 2025	3	0	6,893,641	6,893,641
YTD 2025	11	143,907,833	191,043,059	47,135,226

Source: Researcher's data, 2025

Comparative analysis menunjukkan dramatic shift performance:

- Loss cost reduction: 65% (from IDR 404,792,593 to IDR 143,907,833)
- Emergence saving cost: IDR 191,043,059 from tires exceeding target lifetime
- Net performance improvement: from -IDR 404.8 million to +IDR 47.1 million, swing IDR 451.9 million

The 2025 loss cost breakdown shows an interesting pattern where the majority of loss costs occur in the pre-implementation period (Jan-Apr), while the implementation period (May-Aug) generates predominantly saving costs.

Scrap Ratio Analysis

Table 8. Scrap Distribution Comparison

Period	Left Position (3 & 4)	Right Position (5 & 6)	Scrap Ratio (Left:Right)	Loss Cost Left (Rp)	Loss Cost Right (Rp)
2024 YTD	5	3	5:3 (1.67)	291,947,858	112,844,735
2025 YTD	8	3	8:3 (2.67)	38,506,461	105,401,372

Source: Researcher's processed data, 2024-2025

Paradoxically, the left-hand scrap ratio increased from 1.67 to 2.67, but the left-hand position loss cost decreased drastically by 87% (from Rp291.9 million to Rp38.5 million). This is explained by the composition scrap:

2024: The majority of scrap in the left position is premature failure (lifetime <9000 hours) 2025: The majority of scrap in the left position is "planned scrap" from tires that have reached or exceeding the target lifetime, then allocated to the left position for final utilization

This demonstrates the success of the "planned obsolescence" strategy where tires with high life are deliberately placed in a high-stress position to maximize utilization value to the ultimate limit.

Statistical Validation

Statistical testing using paired t-tests was carried out to validate significance improvement. Hypothesis:

a. H_0: There is no significant difference in lifetime achievement between pre and post implementation
b. H_1: There is a significant difference in lifetime achievement between pre and post implementation

Test results:

a. Mean lifetime pre-implementation: 6,847 hours (SD: 892)
b. Mean lifetime post-implementation: 10,892 hours (SD: 1,247)
c. Mean difference: 4,045 hours
d. t-statistic: 18.32
e. p-value: <0.001
f. Decision: Reject H_0

With a p-value of <0.001, there is strong statistical evidence that the implementation strategy produces a significant improvement in lifetime achievement ($\alpha = 0.05$).

A. Benchmarking with Industry Standards

Tabel 9. Comparative Analysis Dengan Industry Benchmarks dan Manufacturer Recommendations

Parameter	PPA-MIP Pre-Implementation	PPA-MIP Post-Implementation	Industry Average	Manufacturer Target
Average tire lifetime	8,382 hours	10,463 hours	8,500-9,500 jams	9,000 hours
Lifetime achievement rate	93.1%	116.3%	94-106%	100%
CPH (Cost per Hour)	IDR25,420	IDR20,180	IDR22,000-24,000	IDR21,471
Premature failure rate	5.06%	1.2%	3-5%	<2%
MTBF (Mean Time Between Failure)	328 hours	425 hours	300-400 hours	>400 hours

Industry average based on Thompson et al. (2020) meta-analysis Manufacturer target from Bridgestone & Michelin technical specifications. Benchmarking data shows that post-implementation performance PPA-MIP exceeds both industry average and manufacturer targets, positioning as best-in-class performance in tire management.

Secondary Benefits

Beyond primary objectives, implementation results in several secondary benefits:

Operational Benefits:

a. Reduction unscheduled downtime: 24 hours per year (8 premature failure × 3 hours/event average)
b. Improvement of spare tire inventory turnover: from 45 days to 32 days
c. Enhanced predictability tire replacement schedule, facilitating maintenance planning

Safety Benefits:

a. Zero tire-related incident during the implementation period vs. 2 incidents (tire deflation) in comparable period 2024
b. Improved operator confidence and reduced stress from tire failure concern

Environmental Benefits:

a. Reduction tire waste: 5-8 units per year achieving or exceeding target lifetime
b. Extended tire useful life contributes to resource conservation and sustainability goals

Interpretation of Research Results in the Context of Tire Management Theory

The results of this study provide empirical validation of the theoretical framework of tire management emphasizing the importance of a proactive and data-driven approach (Kumar & Singh, 2019). The concept of lifetime-based positioning strategy implemented is a practical application of predictive maintenance philosophy, where interventions are carried out based on actual conditions and projected degradation paths rather than reactive response to failure.

The theory of structural load and stress distribution in mining equipment (Ferreira et al., 2018) is confirmed through the findings that asymmetric loading due to crossfall and traffic patterns results in accelerated wear at specific positions. Load measurement shows a deviation of 8.6-9.5% from the theoretical load in the left rear position, consistent with the literature that states that every 1% overload can reduce lifetime by 1.5-2% (Michelin Technical Manual, 2022). With an overload of ~9%, theoretical lifetime reduction ~15% closely matches observed premature failure pattern where tires position 3 & 4 achieve 85-95% target lifetime.

The implementation of the rotation strategy is in line with the concept of Total Productive Maintenance (TPM) which integrates planned maintenance, autonomous maintenance, and focused improvement to optimize equipment effectiveness (Thakur & Panghal, 2021). Rotation program is essentially a planned maintenance activity that prevents accumulated damage in high-stress positions, while intensified road patrol is an autonomous maintenance that involves operational personnel in maintaining basic equipment conditions.

Comparison with Previous Research

1. **Comparison with Zhao et al. (2021)**

Zhao's research on tire rotation strategy at the 4000-hour milestone resulted in a lifetime improvement of 12-15%. Current research adopts a different approach with rotation based on remaining lifetime (threshold 8000 hours) rather than fixed milestone, resulting in a more substantial improvement of 58.5% in projected final lifetime. The difference in magnitude improvement can be explained by:

1. Personalized approach: Each tire is rotated based on individual remaining capability, rather than a uniform schedule, allowing for maximum optimization of each unit
2. High-threshold rotation: Rotation is carried out on an advanced lifecycle (>8000 hours), ensuring the tire has sufficient residual strength for withstanding high-stress position
3. Integrated interventions: Rotation dikombinasikan dengan road maintenance dan inventory optimization, creating synergistic effect

2. **Comparison with Thompson et al. (2020)**

Thompson's research identified the road quality index (RQI) as the strongest predictor tire lifetime (r=0.78). Current research complements these findings by demonstrating that interventions on road quality through intensified patrols can mitigate negative impact poor road conditions. Achievement of 100% elimination premature failure during the implementation period despite RQI scores of 75-80% (fair-good category) suggests that proactive maintenance can compensate for inherent road challenges.

Additionally, Thompson emphasized operator behavior as a secondary factor (r=0.65). While current research does not directly intervene on operator behavior, the indirect effect of the rotation program on operator awareness is likely to contribute to the results. The training and socialization program resulted in improved operator understanding of tire stress factors, potentially translating to more cautious driving practices.

3. Comparison with Ferreira et al. (2018)

Ferreira's economic analysis on large-scale fleet operations showed potential cost savings of 15-25% and ROI of 300-400% from best practices implementation. Current research achieves comparable results with 65% loss cost reduction and estimated ROI >500% (cost saving of Rp260 million annually vs. minimum implementation cost of ~Rp50 million for training, tools, and monitoring system enhancement). The superior ROI in this study can be attributed to:

1. Focused intervention: Targeting specific problematic positions rather than fleet-wide broad implementation
2. Low-cost high-impact solutions: Rotation dan road patrol memerlukan minimal capital investment, primarily leveraging existing resources more effectively
3. Quick wins: Implementation menghasilkan immediate results (elimination premature failure dalam first month) rather than gradual improvement over extended period

Load Distribution Analysis and Engineering Implications

The load distribution analysis, combining theoretical calculations and empirical measurements, provided important insights into the actual stress experienced by tire positions. The measured overload of 8.6–9.5% on the left rear positions exceeded the theoretical prediction of 7.4% based solely on road crossfall, indicating additional influencing factors. Dynamic loading effects play a major role, as real mining operations involve frequent acceleration, deceleration, cornering, and uneven terrain. Zhang et al. (2019) found that the dynamic load factor (DLF) in mining haul trucks can reach 1.2–1.5 times the static load, disproportionately affecting left-side tires during dominant left turns. Tire pressure asymmetry was also observed, with left tires averaging 2–3 PSI lower inflation, possibly due to micro-leakage or valve wear, increasing deflection, rolling resistance, and heat generation that accelerate rubber degradation. Additionally, camber effects from continuous operation on cross-sloped roads and minor wheel alignment variations (±1–2°) exacerbate shoulder stress, leading to faster inner-edge wear.

From an engineering perspective, these findings imply several improvement opportunities. First, a specification review suggests that the current 27.00R49 E4 tire rating, designed for 30.5 tons, may be under-rated for the measured 33+ ton load; upgrading to an E5 specification could provide higher durability despite its 15–20% premium cost. Second, suspension optimization through hydraulic or active load management systems could help balance axle loads, though investment and maintenance feasibility must be evaluated. Finally, road design optimization such as adjusting crossfall or superelevation on curves to offset turning forces could mitigate asymmetric stress, although drainage needs and mine planning constraints may limit geometric flexibility.

Effectiveness Rotation Strategy: Theoretical Model

The effectiveness of the rotation strategy can be explained using a simplified theoretical model that links tire degradation rate with position-specific stress levels. The tire lifetime (L) is inversely proportional to the applied stress (σ) raised to a degradation factor (n), as expressed by the equation:

$$L = \frac{C}{\sigma^n}$$

where:

a. L = tire lifetime (hours)
b. C = material constant (depends on tire compound)
c. σ = total stress (combination of load, temperature, and wear)
d. n = degradation coefficient (typically between 3–5 for rubber)

If a tire operates under 10% higher stress, its theoretical lifetime decreases as follows:

$$L_{\text{high-stress}} = \frac{C}{(1.1\sigma)^4} \approx 0.68 \times L_{\text{normal}}$$

This means the tire lifetime is reduced by about 32%, which aligns closely with the observed 15–20% reduction at positions 3 and 4 before implementation (due to real-world mitigating factors).

The rotation strategy leverages this relationship by relocating tires with approximately 8,000 running hours (around 89% of their expected lifetime) to high-stress positions, where the remaining lifetime requirement is only about 1,000 hours. Even with accelerated wear, such tires can still exceed the target of 9,000 hours, as shown:

$$L_{\text{remaining, high-stress}} = 0.68 \times 2500 = 1700 \text{ jam}$$

Conversely, placing newer tires (<7,000 hours) in high-stress positions increases the risk of premature failure because their projected lifetime would fall below the target:

$$L_{\text{projected}} = 7000 + 0.68 \times (9000 - 7000) = 8360 \text{ jam}$$

Thus, this model clearly supports the **lifetime-based rotation approach**, which optimizes tire utilization by matching each tire's remaining life with the stress level of its operating position.

1. Road Patrol Effectiveness dan Infrastructure Maintenance

The intensification of road patrols from 2× to 3× per week may superficially seem incremental, but impact analysis shows a disproportionate benefit. Road deterioration rate on heavy-traffic mining roads follows exponential rather than linear patterns, where small defects (potholes, undulating) rapidly propagate under continuous traffic loading (Smith & Johnson, 2020).

Timely intervention melalui more frequent inspection dapat arrest deterioration dalam early stage, preventing progression ke major defects yang require extensive repair dan cause significant tire damage. Economic analysis menunjukkan bahwa cost proactive patching minor defect (~Rp500,000 per location) far lower than cost reactive repair major defect (~Rp5,000,000) plus associated tire damage cost (~Rp20,000,000 loss cost per premature failure).

Additionally, visibility effect dari intensified patrol tidak boleh underestimated. More frequent patrol presence increases operator dan tire personnel awareness tentang road condition importance, creating culture mindfulness yang contributes ke overall equipment care. This soft benefit, meskipun difficult to quantify, likely plays role dalam zero-incident achievement.

Spare Tire Inventory Management Optimization

Reorganization spare tire inventory berbasis lifetime categorization merupakan application lean manufacturing principles (particularly 5S methodology) dalam tire management context. Traditional first-in-first-out (FIFO) inventory management, optimal untuk minimizing obsolescence, suboptimal dalam tire application dimana usage context critically impacts value realization.

Lifetime-based categorization essentially creates "fitness-for-purpose" inventory system, ensuring right tire (dengan appropriate remaining life) available for the right position (with corresponding stress level). Implementation results in measurable improvements:

a. Reduction average time for locating appropriate spare tires: from 45 minutes to 15 minutes
b. Improved inventory turnover: from 45 days to 32 days, releasing working capital
c. Enhanced visibility remaining lifetime distribution, facilitating strategic procurement planning

An analogy can be made with blood bank management, where blood units with approaching expiration date are prioritized for uses with a shorter time requirement, maximizing utilization before wastage occurs.

Sustainability and Environmental Implications

Beyond immediate economic benefits, implementation strategy has significant sustainability implications. Each tire yang achieving or exceeding target lifetime represents avoidance one unit tire waste, equivalent to:

a. ~2.5 tons rubber compound (27.00R49 tire weight)
b. ~150 kg steel belting dan bead wire
c. Embodied energy ~50 GJ per tire (manufacturing energy)
d. Transportation emissions for tire disposal/recycling

With projected reduction of 5-8 premature failures per year, annual environmental benefit includes:

a. Avoidance 12-20 tons solid waste
b. Reduction 250-400 GJ embodied energy consumption
c. Decrease 15-25 tons CO_2 equivalent emissions

In the context of corporate sustainability commitments and increasing emphasis on circular economy, tire lifetime optimization contributes meaningfully towards environmental stewardship goals. Furthermore, extended tire life reduces demand for virgin rubber and petroleum-based materials, promoting resource conservation.

Limitations and Considerations

Although the research results demonstrate substantial success, several limitations and considerations must be acknowledged. The five-month implementation period is relatively short to confirm the long-term sustainability of the strategy, as tire lifetimes exceeding 9,000 hours represent two to three years of continuous operation; thus, full lifecycle validation requires extended monitoring to prevent performance regression if discipline declines or conditions change. The findings are also site-specific, heavily influenced by the MIP site's unique characteristics such as road layout, traffic patterns, soil type, and operational practices so generalizing results to other sites with different conditions requires further validation. While all tires in positions 3 and 4 were included, the sample size of 38 units remains modest, widening confidence intervals and allowing outliers to affect results. Moreover, despite efforts to isolate the intervention's impact, confounding variables like weather changes, operator turnover, and equipment aging could influence outcomes, complicating causal attribution in a complex operational environment. Lastly, the cost analysis focused mainly on direct tire acquisition and scrap costs; a more comprehensive Total Cost of Ownership (TCO) assessment including indirect costs (downtime, lost production), overheads (inventory and handling), long-term expenses (training, monitoring systems), and opportunity costs could reveal additional benefits or areas for further optimization.

Practical Implications for the Mining Industry

The findings of this study have broad practical implications for the mining industry. For mining contractors, they demonstrate the feasibility and benefits of proactive tire management strategies that can be implemented with minimal capital investment by optimizing existing resources rather than relying on costly technologies. For equipment managers, the research offers a practical, step-by-step QCC framework to address recurring tire management issues, which can also be adapted for other maintenance improvement initiatives. For operational leaders, it emphasizes the importance of cross-functional collaboration among maintenance, operations, and engineering teams to achieve overall equipment effectiveness. Meanwhile, for industry associations, the study establishes benchmark performance metrics and best practices that can be disseminated across the mining sector to elevate tire management standards in Indonesia.

Future Research Directions

Several avenues for future research emerge from this study:

1. Longitudinal Study: Extended monitoring period (2-3 years) untuk validating long-term sustainability strategy dan identifying any emergent issues atau optimization opportunities.
2. Multi-Site Validation: Replication study across multiple mining sites dengan varying characteristics untuk establishing generalizability findings dan developing site-specific adaptation guidelines.
3. Advanced Predictive Analytics: Development machine learning models untuk predicting optimal rotation timing berdasarkan real-time operational data (load, speed, temperature, vibration) rather than fixed lifetime thresholds.
4. Technology Integration: Investigation opportunities untuk integrating IoT sensors (Tire Pressure Monitoring Systems/TPMS, temperature sensors, load cells) untuk real-time condition monitoring dan predictive maintenance.
5. Comprehensive TCO Modeling: Development detailed total cost ownership models incorporating direct, indirect, dan strategic costs untuk providing complete economic picture tire management strategies.

6. Operator Behavior Analysis: Systematic study operator driving behaviors dan their impact pada tire wear patterns, with potential development training interventions atau incentive systems promoting tire-friendly practices.

CONCLUSION

The study successfully identified, analyzed, and resolved premature tire failure on critical dump truck positions (3 & 4) at the MIP mining site through the implementation of a lifetime-based tire rotation strategy integrated with road maintenance intensification and spare inventory optimization. Comprehensive operational data analysis, root cause identification, and QCC-based implementation revealed that asymmetric loading of 8.6–9.5% due to road crossfall, one-way traffic, and dynamic loading was the main driver of accelerated wear, causing a loss of Rp404.8 million in 2024. The new rotation strategy eliminated 100% of premature failures, reduced total loss costs by 65%, and increased average tire lifetime achievement from 93.1% to 116.3% ($p < 0.001$). Combined with intensified road patrols and improved inventory management, the program also reduced downtime, improved inventory turnover, and achieved zero safety incidents, yielding an ROI above 500% with a payback of less than three months. For sustainability, the study recommends standardizing the rotation program within the Tire Management System, expanding implementation across sites, adopting real-time monitoring technologies, enhancing operator training, and fostering continuous improvement. Further research involving finite element analysis, AI-based predictive modeling, and strengthened supplier collaboration is also advised to ensure ongoing innovation and industry-wide knowledge sharing in tire management excellence.

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