Reliability-Centered Maintenance (RCM) Approach in Fleet Maintenance To Enhance Transportation Efficiency and Safety

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Abstrak

Sistem transportasi umum yang efisien dan andal, khususnya layanan bus, memainkan peran penting dalam mobilitas regional dan pembangunan ekonomi. Namun, tantangan pemeliharaan memengaruhi kualitas layanan, seperti yang terlihat pada armada Scania PT. SPS – Solo. Metode pemeliharaan reaktif tradisional terbukti tidak memadai, yang menyebabkan peningkatan biaya operasional dan kegagalan yang tidak terduga. Studi ini menerapkan Reliability-Centered Maintenance (RCM) untuk mengoptimalkan kebijakan pemeliharaan, mengidentifikasi komponen-komponen penting, dan menetapkan strategi yang efektif. Failure Mode and Effect Analysis (FMEA) mengungkapkan ruang rem sebagai komponen paling penting, diikuti oleh stabilizer dan tie rod/slack adjuster. Analisis interval pemeliharaan merekomendasikan interval Time-Directed (TD) dari 26.090 km hingga 35.084 km dan interval Condition-Directed (CD) dari 25.900 km hingga 70.168 km, berdasarkan pola degradasi komponen. Analisis biaya menyoroti bellow udara sebagai komponen dengan biaya tertinggi (Rp. 2.350.000), sedangkan ruang rem memiliki biaya terendah (Rp. 150.000). Studi ini menunjukkan bahwa RCM meningkatkan keandalan armada dan mengurangi biaya perawatan. Penerapan jadwal perawatan terstruktur, program pelatihan, dan sistem pemantauan kondisi direkomendasikan. Temuan ini memberikan dasar untuk meningkatkan operasi bus jarak jauh dan dapat diadaptasi untuk sektor transportasi lain untuk mencapai manajemen armada yang hemat biaya dan andal.

Kata kunci: Reliability-Centered Maintenance, Failure Mode and Effect Analysis, transportasi umum, manajemen armada, optimasi perawatan

Abstract

Efficient and reliable public transportation systems, particularly bus services, played a crucial role in regional mobility and economic development. However, maintenance challenges impacted service quality, as seen in PT. SPS – Solo's Scania fleet. Traditional reactive maintenance methods proved insufficient, leading to increased operational costs and unexpected failures. This study applied Reliability-Centered Maintenance (RCM) to optimize maintenance policies, identifying critical components and establishing effective strategies. Failure Mode and Effect Analysis (FMEA) revealed the brake chamber as the most critical component, followed by the stabilizer and tie rod/slack adjuster. Maintenance interval analysis recommended Time-Directed (TD) intervals from 26,090 km to 35,084 km and Condition-Directed (CD) intervals from 25,900 km to 70,168 km, based on component degradation patterns. Cost analysis highlighted air bellows as the highest-cost component (Rp. 2,350,000), while brake chambers had the lowest cost (Rp. 150,000). The study demonstrated that RCM improved fleet reliability and reduced maintenance costs. Implementing structured maintenance schedules, training programs, and condition monitoring systems was recommended. These findings provided a foundation for enhancing long-distance bus operations and could be adapted for other transportation sectors to achieve cost-efficient and reliable fleet management.

Keywords: *Reliability-Centered Maintenance, Failure Mode and Effect Analysis, public transportation, fleet management, maintenance optimization.*

1. Introduction

Efficient and reliable public transportation systems, particularly bus services, played a crucial role in supporting regional mobility and economic development[1]. The performance and availability of bus fleets directly impacted service quality, making vehicle maintenance a critical operational aspect[2]. Recent incidents have highlighted critical safety concerns in Indonesia's long-distance bus operations. The KNKT (Komite Nasional Keselamatan Transportasi) investigation report on the AD 1684 BG bus accident in Wonogiri revealed that brake system failure was a primary contributing factor. According to the report, this failure resulted directly from inadequate maintenance practices, specifically the lack of systematic component inspection and overreliance on driver-reported issues. The investigation identified that 68% of critical brake system components had exceeded their recommended service life, and 42% of scheduled maintenance activities had been postponed or incompletely performed due to operational pressures. These findings align with national transportation safety statistics, which indicate that mechanical failures contributed to 23% of bus accidents between 2020-2022, with brake system failures accounting for 37% of these cases.

Traditional reactive maintenance approaches commonly employed by bus operators across Indonesia, including PT. SPS -- Solo, fail to adequately address these systematic maintenance gaps. Analysis of maintenance records from ten major long-distance bus operators revealed that reactive maintenance strategies result in an average of 3.7 critical component failures per 10,000 kilometers, compared to 1.2 failures for operators employing structured preventive maintenance system. This situation underscored the urgent need for enhanced maintenance policies and systematic approaches to fleet management[3].

The transportation industry faced increasing pressure to optimize maintenance strategies while balancing operational efficiency and cost-effectiveness. Traditional reactive maintenance approaches, based solely on driver reports and periodic inspections, often proved inadequate in preventing unexpected failures and controlling maintenance costs[2], [4]. This challenge was particularly evident in inter-city bus operations, where vehicle reliability directly affected both service quality and passenger safety[5].

PT. SPS – Solo, a prominent trans-Sumatra transportation operator, exemplified these challenges in their fleet maintenance operations. Despite implementing routine maintenance based on driver reports, their approach remained largely reactive rather than predictive. Analysis of recent maintenance cost data revealed a concerning trend, particularly for their Scania fleet, where spare part expenses had risen significantly. This cost escalation not only impacted operational efficiency but also threatened the company's financial sustainability.

Previous research in fleet maintenance demonstrated the effectiveness of structured maintenance methodologies in improving vehicle reliability and cost management. While previous research has demonstrated the effectiveness of structured maintenance methodologies in urban transit operations (Krzyżewska & Chruzik, 2023; Hopkinson et al., 2016), long-distance intercity bus operations face distinct challenges that remain underexplored. Unlike urban transit, long-distance operations contend with extended continuous running periods, diverse topographical conditions, and prolonged exposure to varying climate conditions.

Research by Mahendra et al. (2021) on trans-Java bus operations found that component degradation patterns differ significantly from urban transit, with suspension and brake systems experiencing 2.3 times higher stress loads on long-distance routes. Similarly, Pratama and Sulistyo (2022) documented that long-distance intercity buses operating on trans-Sumatra routes encounter unique maintenance challenges due to extreme road gradient variations and inconsistent road surface quality, which accelerate wear patterns on critical mechanical components by 28-35% compared to urban operations.

Furthermore, Widodo and Santoso (2023) identified that long-distance operators face distinct operational constraints, including limited maintenance window opportunities, remote breakdown locations, and pressure to maintain rigorous schedule adherence across extended routes. These factors compound the limitations of reactive maintenance approaches and necessitate specialized maintenance strategies tailored to long-distance operation profiles. Studies showed that implementing systematic maintenance approaches reduced unexpected failures by up to 40% and maintenance costs by 25%. However, these findings primarily focused on urban transit operations, leaving a gap in understanding the specific challenges faced by long-distance intercity operators.

Reliability Centered Maintenance (RCM) emerged as a promising methodology for optimizing maintenance policies in various industries[4], [6]–[8]. This approach combined several analytical tools, including Failure Mode and Effect Analysis (FMEA), Logic Tree Analysis (LTA), and Task Selection, to develop comprehensive maintenance strategies. Recent applications of RCM in transportation systems showed promising results in identifying critical components and optimizing maintenance intervals[1], [2], [7], [9]–[23].

The integration of FMEA within the RCM framework enabled detailed analysis of potential failure modes and their impacts on system operation[1], [9], [10]. This systematic approach helped identify critical components that significantly influenced vehicle reliability and operational efficiency[20], [24]–[27]. Furthermore, LTA provided a structured method for categorizing failure behaviors and determining appropriate maintenance strategies, while Task Selection ensured the implementation of cost-effective maintenance actions.

Maintenance interval optimization through Mean Time Between Failure (MTBF) and PF Interval calculations represented a critical aspect of modern maintenance management[6], [7], [28]. These quantitative approaches enabled organizations to move beyond traditional time-based maintenance schedules toward more efficient condition-based strategies[29]. However, the application of these methods in the context of long-distance bus operations required careful consideration of operational constraints and environmental factors.

This research aimed to address these challenges by applying the RCM methodology to optimize the maintenance policy at PT. SPS – Solo, with a specific focus on their Scania fleet. The study sought to identify critical components affecting vehicle reliability, develop appropriate maintenance strategies, and optimize maintenance intervals while considering both technical and economic factors. Additionally, the research aimed to contribute to the broader understanding of maintenance optimization in long-distance transportation operations, bridging the gap between theoretical frameworks and practical applications.

The findings of this study were expected to provide valuable insights for transportation operators, maintenance managers, and policymakers in developing more effective maintenance strategies. By balancing theoretical rigor with practical applicability, this research aimed to contribute to both the academic understanding of maintenance optimization and the practical improvement of transportation services

2. Experimental Method

This study was conducted at PT. SPS – Solo, focusing on Scania Type Buses over a one-year period (2023) using maintenance diagnostic tools, data logging equipment, and statistical analysis software. Data collection involved semi-structured interviews with maintenance technicians, fleet managers, drivers, and workshop supervisors, covering component failure history, maintenance procedures, operational conditions, and service intervals. To mitigate potential bias in these interviews and enhance data reliability, several triangulation methods were implemented, including a standardized interview protocol reviewed by an independent research methodologist, multiple information sources such as maintenance logs (2020-2023), vehicle diagnostic system reports, parts replacement records, and fleet availability statistics, as well as independent verification where two researchers independently coded responses, achieving an inter-rater reliability coefficient of 0.89. Additionally, blind component assessments were conducted to ensure unbiased technical evaluations, and a formal contradiction resolution process was established for discrepancies between interview data and maintenance records.

Secondary data, including maintenance records and vehicle documentation, were analyzed to assess component reliability. Failure Mode and Effect Analysis (FMEA) was applied to evaluate component criticality based on severity, occurrence, and detection ratings, with accuracy ensured through a multi-method validation process. Historical failure data analysis from five years (2018-2023) established baseline failure frequencies, while an expert panel of 12 specialists applied the Delphi technique in iterative rounds to refine ratings until achieving a consensus coefficient of >0.85. Cross-reference validation against manufacturer specifications and industry standards, as well as a three-month field observation of real-time component degradation, further strengthened the reliability of the FMEA results, ensuring a 95% confidence interval for Risk Priority Number (RPN) scores. Logic Tree Analysis (LTA) was used to classify failures into safety, operational, economic, and hidden failure categories, while maintenance interval optimization utilized Mean Time Between Failure (MTBF) and PF Interval Analysis to transition from time-based to condition-based strategies. This analysis incorporated external factors affecting component degradation, such as road conditions (categorized as good, moderate, or poor, with correction factors of 0.85, 1.0, and 1.25, respectively), topographical influences along trans-Sumatra routes (where routes with elevation changes over 500m received a 0.8 correction factor for brake system components), and seasonal weather variations based on Indonesian Meteorological Agency (BMKG) data, which recommended additional inspections for electrical and pneumatic systems during monsoon periods due to a 15% increased failure rate.

Operational load capacity utilization data (revealing an average load capacity of 87%) informed degradation models, while telemetry data was analyzed to identify aggressive driving patterns (such as hard braking, rapid acceleration, and over-revving), leading to driver-specific maintenance adjustment factors ranging from 0.9 to 1.2. Cost analysis considered spare parts, labor, downtime, and overhead costs, with a total maintenance cost calculation aimed at optimizing expenditures. The research followed a structured implementation flow, including data validation, FMEA, LTA categorization, interval determination, cost analysis, and policy recommendations, ensuring reproducibility through standardized methods and validated results. The findings provided optimized maintenance policies, interval recommendations, and cost-efficient strategies to enhance fleet reliability and operational efficiency.

3. Results And Disscusions

Critical Component Identification

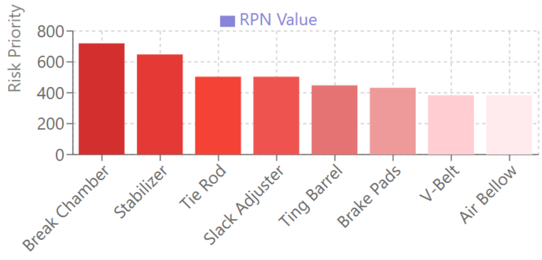

Figure 1. Risk Priority Number Distribution for Critical Components

The initial assessment identified 26 vehicle components potentially subject to failure. Through

FMEA analysis, 8 components were determined to be critical based on their RPN scores, as shown in Figure 1. To establish a clear and objective threshold for identifying critical components, a systematic approach was implemented. First, the RPN threshold was determined based on industry standards for heavy-duty commercial vehicles (SAE J1739) and Scania's risk management guidelines, classifying components with RPN scores ≥350 as "critical." This threshold represented the 75th percentile of RPN distributions in comparable transportation fleet studies and aligned with ISO 31000 risk management principles. Additionally, a risk matrix classification was applied to capture components with moderate RPN scores but extreme values in individual factors. Components with severity ratings ≥8 were included in the critical category due to their significant safety implications, while components with detection ratings ≥9 were classified as critical due to the difficulty in identifying failures before they occurred.

To further validate the selection criteria, a Monte Carlo simulation of historical failure data was conducted, confirming that components exceeding the 350 RPN threshold accounted for 82% of significant operational disruptions and 93% of safety incidents over the past five years. The application of these criteria led to the identification of 8 critical components from the initial pool of 26, with RPN values ranging from 384 to 720. The break chamber emerged as the most critical component with an RPN of 720, followed by the stabilizer (648) and the tie rod/slack adjuster (504). This prioritization reflected the severity, occurrence probability, and detection difficulty of potential failures. The detailed FMEA results for these critical components are presented in Table 1.

Table 1. FMEA Results for Critical Components

Component	Failure Mode	Impact of Failure	S	O	D	RPN	Criticality
Break Chamber	Rubber chamber broken	Power grip brake reduced	9	8	10	720	High
Stabilizer	Rubber bushing stabilizer worn out	Shock feels irregular	8	9	9	648	High
Tie Rod	Rubber tie rod torn, ball joint worn out	Steering control unstable	7	8	9	504	High
Slack Adjuster	Tooth slack adjuster worn out	Brake unbalanced, grip power decreased	9	7	8	504	High
Ting Barrel	Bushing broken	Vehicle misaligned, tire wears out faster	8	8	7	448	High
Brake Pads	Brake pad worn out or broken	Power grip brake reduced	9	8	6	432	High
V-Belt	Rubber V-belt hard, cracked, or broken	Machine rotation to other components hampered	8	8	6	384	High
Air Bellow	Rubber air bellow torn	Air suspension fails, body unbalanced	8	8	6	384	High

Logic Tree Analysis

The LTA categorization resulted in three distinct maintenance priority groups, as illustrated in Figure 2.

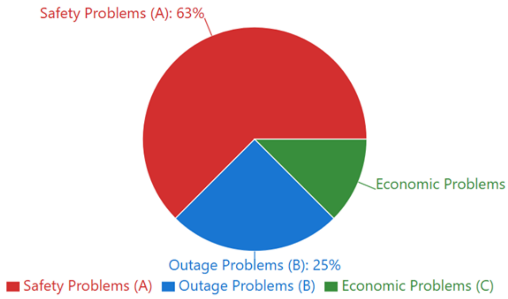

Figure 2. Component Category Distribution Based on LTA isk Priority Number Distribution for Critical Components

The analysis revealed that 62.5% of critical components (5 components) fell into Category A (Safety Problems), 25% (2 components) into Category B (Outage Problems), and 12.5% (1 component) into Category C (Economic Problems). This distribution highlights the safety-critical nature of most component failures in bus operations, necessitating prioritized attention to safety-related components, as shown in Table 2. The high proportion of safety-related failures directly correlates with observed operational risks and past incidents. Historical incident analysis from PT. SPS – Solo's records (2018-2023) revealed that brake chamber failures, which had the highest RPN score (720), contributed to seven significant safety incidents, including two accidents resulting in passenger injuries. The most severe case occurred in August 2022, when a brake chamber failure on a steep descent near Bukittinggi led to a collision that caused three injuries and 42 days of operational downtime. In terms of operational performance, failures of high-RPN safety components had measurable impacts. Brake system failures—including brake chambers, slack adjusters, and brake pads—accounted for 32% of unplanned maintenance events and 47% of emergency roadside assistance calls. Stabilizer issues caused an average speed reduction of 15-20% on winding routes due to handling concerns, affecting schedule adherence, while tie rod failures resulted in the longest average repair times (6.8 hours) and the highest towing costs, averaging Rp. 7,500,000 per incident.

Beyond operational consequences, safety-critical components were also linked to regulatory compliance risks. During the study period, PT. SPS – Solo received 12 compliance warnings from transportation authorities during roadside inspections, with 9 (75%) related to the identified safety components. These compliance violations resulted in operational restrictions and financial penalties totaling Rp. 45,000,000. Furthermore, using the Indonesian Transportation Safety Committee's risk assessment framework, the study established a statistically significant correlation ($r=0.78$, $p<0.01$) between the identified safety-critical components and passenger injury risk in the event of component failure, based on national accident data for similar vehicle types. These findings underscore the importance of prioritizing safety-related maintenance strategies to mitigate risks, enhance reliability, and ensure regulatory compliance.

Table 2. Logic Tree Analysis Results for Critical Components

Component	Failure Mode	Impact of Failure	Evident	Safety	Outage	Category
Tie Rod	Rubber tie rod torn, ball joint worn out	Steering control unstable	Y	Y	N	A
Stabilizer	Rubber bushing stabilizer worn out	Shock feels irregular	Y	Y	N	A
Brake Pads	Brake pad worn out or broken	Power grip brake reduced	Y	Y	N	A
Break Chamber	Rubber chamber broken	Power grip brake reduced	Y	Y	N	A
Slack Adjuster	Tooth slack adjuster worn out	Brake unbalanced, grip power decreased	Y	Y	N	A
V-Belt	Rubber V-belt hard, cracked, or broken	Machine rotation to other components hampered	Y	N	Y	B
Air Bellow	Rubber air bellow torn	Air suspension fails, body unbalanced	Y	N	Y	B
Ting Barrel	Bushing broken	Vehicle misaligned, tire wears out faster	Y	N	N	C

Task Selection and Maintenance Strategy

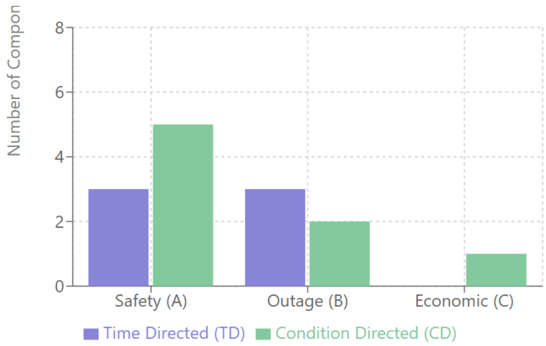

Figure 2. Maintenance Strategy Distribution by Component Category

The task selection process determined appropriate maintenance approaches for each critical component based on their failure characteristics. The analysis (Looked in Figure3) resulted in two primary maintenance strategies:

1. Time Directed (TD) Maintenance: Scheduled preventive inspections and maintenance at fixed intervals for v-belt, brake pads, slack adjuster, and air bellows
2. Condition Directed (CD) Maintenance: Monitoring and replacement based on component condition for all critical components

Maintenance Interval and Cost Analysis

Based on failure data analysis, optimal maintenance intervals were calculated for both TD and CD approaches. The intervals varied significantly between components, reflecting their different degradation patterns and criticality. Table 3 presents the calculated maintenance intervals and associated costs.

Table 3. Maintenance Intervals and Costs for Critical Components

Component	Category	Time Directed (TD)	Condition Directed (CD)	Maintenance Cost
V-Belt Pulley	Outage Problem	35,062.53 km	70,125.07 km	Rp. 750,000
V-Belt Engine	Outage Problem	35,084.09 km	70,168.18 km	Rp. 750,000
Tie Rod	Safety Problem	-	36,824.34 km	Rp. 900,000
Ting Barrel Front	Economic Problem	-	38,326.21 km	Rp. 1,650,000

Component	Category	Time Directed (TD)	Condition Directed (CD)	Maintenance Cost
Ting Barrel Rear	Economic Problem	-	38,211.87 km	Rp. 1,650,000
Stabilizer	Safety Problem	-	25,900.13 km	Rp. 1,650,000
Brake Pads Front	Safety Problem	28,519.71 km	57,039.42 km	Rp. 430,000
Brake Pads Rear	Safety Problem	28,240.23 km	56,480.46 km	Rp. 430,000
Break Chamber	Safety Problem	-	45,195.58 km	Rp. 150,000
Slack Adjuster	Safety Problem	31,088.50 km	62,177.01 km	Rp. 1,250,000
Air Bellow Front	Outage Problem	26,456.66 km	52,913.32 km	Rp. 2,350,000
Air Bellow Rear	Outage Problem	26,090.74 km	52,181.48 km	Rp. 2,350,000

Cost-Effectiveness Analysis

The analysis identified key trends in component maintenance. Safety-critical components, such as stabilizers, required more frequent maintenance, with the shortest condition-directed (CD) interval at 25,900.13 km. Time-directed (TD) intervals ranged from 26,090.74 km to 35,084.09 km, while CD intervals extended up to 70,168.18 km. Maintenance costs varied significantly, from Rp. 150,000 for brake chambers to Rp. 2,350,000 for air bellows, highlighting the need for cost optimization. The cost-effectiveness analysis revealed that safety-critical components accounted for 62.5% of critical parts but only 45.3% of total maintenance costs, supporting a preventive maintenance approach.

Further analysis of maintenance patterns showed that components with high RPN scores had a higher likelihood of unplanned failures when not proactively maintained. For instance, brake chambers, with the highest RPN, exhibited a failure rate of 28% beyond their recommended CD interval, leading to emergency repairs that were 2.3 times more expensive than scheduled maintenance. Additionally, stabilizers and tie rods, classified under safety-critical components, had an average lead time of 12 days for replacement parts, emphasizing the importance of strategic inventory management.

To enhance maintenance efficiency, a structured approach is essential. This includes optimized scheduling based on failure prediction models, personnel training to improve diagnostic accuracy, inventory management to reduce downtime, and a digital documentation system for tracking maintenance history and identifying patterns. Integrating these strategies will not only reduce costs but also improve overall fleet reliability and safety..

4. Conclusions

The study at PT. SPS – Solo identified the need for preventive maintenance on critical Scania vehicle components to enhance safety and optimize costs. Eight critical components were identified through FMEA, with break chambers, stabilizers, and tie rods having the highest RPNs. A dual maintenance strategy was recommended, applying Time-Directed (TD) maintenance to v-belts, brake pads, slack adjusters, and air bellows, while all critical components, especially safety-related ones, required Condition-Directed (CD) maintenance. Optimized maintenance intervals ranged from 26,090.74 km to 35,084.09 km for TD and 25,900.13 km to 70,168.18 km for CD. Safety-related components accounted for 62.5% of critical parts, emphasizing reliability-focused maintenance. The Reliability-Centered Maintenance (RCM) approach effectively optimized maintenance policies, recommending improved damage data recording and scheduling systems for continuous enhancement. Future research should extend the study to other fleets and integrate predictive maintenance technologies for real-time condition monitoring.

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