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Railway Safety, Railway Signaling System Evaluation, Cicalengka Accident Mitigation, and Railway Travel Procedure Updates

Keselamatan Kereta Api, Evaluasi Sistem Persinyalan Kereta Api, Mitigasi Kecelakaan Cicalengka, dan Pembaharuan Prosedur Perjalanan Perkeretaapian

Amanda Mega Riyadi, Deta Sulistiyo Tjaedi, Ramadhan Arya Prayoga
[1]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW.3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia
[2]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW.3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia
[3]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW.3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia
[4]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW.3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia

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Abstract

study evaluates changes to the railway signaling system on the Cicalengka route following an accident incident to enhance railway operational safety and reliability. The research background is based on the critical importance of signaling systems in accident prevention. The literature review examines railway signaling system developments, accident causation analysis, and international safety standards. The methodology employs a case study with qualitative and quantitative approaches, including analysis of accident investigation documents, field observations, interviews with operational staff, and system performance simulation. Results indicate that the implemented signaling system changes—covering interlocking upgrades, addition of automatic train protection (ATP), and communication procedure modifications—have improved safety factors by 47%. Analysis of post-implementation operational disturbance data shows a 68% reduction in near-miss incidents over a six-month period. The study concludes that integrating advanced signaling technology with comprehensive procedural training significantly reduces operational risks, although continuous evaluation is needed to address technical and human resource challenges. This research contributes to transportation systems engineering literature by providing a post-incident evaluation model adaptable to Indonesian railway infrastructure contexts.

Keywords: *Railway Signaling System, Railway Safety, Accident Mitigation.*

Abstrak

Penelitian ini mengevaluasi perubahan sistem persinyalan kereta api di lintas Cicalengka pasca insiden kecelakaan untuk meningkatkan keamanan dan keandalan operasi perkeretaapian.

Latar belakang penelitian didasarkan pada pentingnya sistem persinyalan sebagai komponen kritis dalam pencegahan kecelakaan. Tinjauan pustaka mengkaji perkembangan sistem persinyalan kereta api, analisis penyebab kecelakaan, dan standar keselamatan internasional. Metodologi yang digunakan adalah studi kasus dengan pendekatan kualitatif dan kuantitatif, meliputi analisis dokumen investigasi kecelakaan, observasi lapangan, wawancara dengan petugas operasional, dan simulasi kinerja sistem. Hasil penelitian menunjukkan bahwa perubahan sistem persinyalan yang diimplementasikan— meliputi peningkatan interlocking, penambahan automatic train protection (ATP), dan modifikasi prosedur komunikasi—telah meningkatkan faktor keamanan sebesar 47%. Analisis data gangguan operasional pasca- implementasi menunjukkan penurunan insiden hampir-signal (near-miss) sebesar 68% dalam periode enam bulan.
Simpulan penelitian mengkonfirmasi bahwa integrasi teknologi sinyal mutakhir dengan pelatihan prosedural yang komprehensif secara signifikan mengurangi risiko operasional, meskipun diperlukan evaluasi berkelanjutan untuk menghadapi tantangan teknis dan sumber daya manusia. Penelitian ini berkontribusi pada literatur rekayasa sistem transportasi dengan memberikan model evaluasi pasca-insiden yang dapat diadaptasi untuk konteks infrastruktur kereta api Indonesia.

Kata Kunci: Sistem Persinyalan Kereta Api, Keselamatan Kereta Api, Mitigasi kecelakaan.

1. Introduction

1.1 Railway Transportation and the Imperative of Safety

Railway transportation has long been recognized as a backbone of national and regional mobility systems. It supports economic growth by facilitating the movement of people and goods with high efficiency, relatively low energy consumption, and reduced environmental impact compared to road and air transport. In many developing and developed countries alike, railways play a strategic role in connecting metropolitan areas with suburban and rural regions, ensuring equitable access to transportation services.

Despite these advantages, railway operations inherently involve high levels of risk due to the large mass of rolling stock, high operating speeds, and complex interactions between infrastructure, technology, and human operators. Any failure within this interconnected system may lead to severe consequences, including loss of life, infrastructure damage, service disruption, and erosion of public trust. As traffic density increases and operational demands grow, ensuring railway safety becomes not only a technical necessity but also a social and ethical obligation.

Safety in railway systems is therefore not an isolated objective but a continuous process that requires systematic planning, implementation, monitoring, and improvement. Modern railway safety frameworks emphasize prevention rather than reaction, recognizing that accidents are often the result of latent system weaknesses rather than isolated human errors.

1.2 Evolution of Railway Safety Concepts

Historically, railway safety relied heavily on mechanical safeguards and human vigilance. Early signaling systems used manual flagging and mechanical semaphores, while train separation depended largely on time intervals and operator judgment. Although these methods were effective in early railway operations, increasing speeds and traffic volumes exposed their limitations.

Over time, safety concepts evolved toward the adoption of block systems, interlocking mechanisms, and automatic train protection. The contemporary approach to railway safety is rooted in systems engineering, where safety is designed into every stage of planning, construction, operation, and maintenance. International standards emphasize risk-based safety management systems (SMS), which integrate technical controls, operational procedures, and organizational culture into a unified framework.

This evolution highlights the importance of continuous evaluation and adaptation, particularly in countries where railway infrastructure combines legacy systems with newer technologies.

1.3 Signaling Systems as the Core of Operational Safety

Railway signaling systems are fundamental to the safe regulation of train movements. They provide authority for train operations, prevent conflicting routes, and ensure adequate separation between trains. Signaling systems encompass a wide range of technologies, including fixed and moving block systems, track circuits, axle counters, electronic interlocking, centralized traffic control, and onboard automatic protection systems.

In high-density railway networks, the reliability of signaling systems directly determines operational safety margins. Even minor failures or delays in signal information can cascade into hazardous situations. Consequently, systematic evaluation of signaling performance—covering hardware reliability, software integrity, communication accuracy, and human-machine interfaces—is essential.

The transition from conventional signaling to digital and automated systems introduces new safety challenges, including cybersecurity risks, software validation requirements, and operator adaptation. These factors reinforce the need for comprehensive evaluation frameworks that address both traditional and emerging risks.

1.4 Human Factors in Railway Safety Systems

While technology plays a crucial role, human operators remain central to railway safety. Train drivers, dispatchers, signal operators, maintenance personnel, and supervisors must interpret information, make decisions, and execute actions under time pressure and operational constraints. Human factors such as fatigue, stress, situational awareness, and communication effectiveness significantly influence safety outcomes.

Modern accident investigations consistently demonstrate that accidents rarely result from a single mistake. Instead, they arise from a combination of human, technical, and organizational failures. Therefore, railway safety strategies increasingly incorporate human factors engineering, ergonomic system design, and competency-based training programs.

A safety-oriented organization fosters an environment where personnel are encouraged to report hazards and near-miss incidents without fear of punishment. Such reporting mechanisms enable early identification of systemic weaknesses before they lead to serious accidents.

1.5 Railway Accidents as Learning Opportunities

Major railway accidents serve as critical learning opportunities for improving safety systems. Each accident reveals underlying vulnerabilities in technology, procedures, and organizational practices. Systematic accident analysis allows stakeholders to identify root causes, contributing factors, and effective countermeasures.

In Indonesia, several railway accidents have prompted regulatory reforms and infrastructure improvements. Among these, the Cicalengka train accident stands out due to its operational complexity and safety implications. The incident highlights the interplay between signaling limitations, operational decision-making, and emergency response effectiveness.

1.6 Overview of the Cicalengka Train Accident

The Cicalengka area represents a strategically important railway corridor with high traffic density. The accident that occurred in this area exposed deficiencies in signaling coordination, operational supervision, and procedural compliance. Although immediate causes may be identified, a deeper systems-based analysis reveals multiple layers of contributing factors.

Understanding the Cicalengka accident requires examining not only technical failures but also contextual elements such as workload, communication protocols, infrastructure constraints, and organizational safety culture. This comprehensive perspective is essential for developing effective mitigation strategies.

1.7 Accident Mitigation and Risk Management Approaches

Accident mitigation in railway systems involves identifying hazards, assessing risks, and implementing controls to reduce the likelihood and severity of accidents. Risk management tools such as hazard identification (HAZID), hazard and operability studies (HAZOP), and failure mode and effects analysis (FMEA) are widely used in railway safety engineering.

Mitigation measures may include technological upgrades, procedural changes, organizational restructuring, and enhanced training. Importantly, mitigation strategies must be continuously reviewed and updated based on operational experience and emerging risks.

1.8 Emergency Response and Resilience

Beyond prevention, railway safety systems must ensure effective response when accidents occur. Emergency preparedness includes clear communication protocols, coordination with external emergency services, and regular drills. Rapid and coordinated response can significantly reduce casualties and secondary impacts.

Resilience in railway systems refers to the ability to absorb disturbances, adapt to abnormal conditions, and recover quickly from disruptions. Building resilience requires redundancy, flexibility, and robust decision-making frameworks.

1.9 Procedural Frameworks in Railway Operations

Operational procedures translate safety principles into daily practice. They govern train dispatching, signaling operations, maintenance activities, and emergency handling. Well-designed procedures reduce ambiguity and ensure consistent responses across the organization.

However, procedures must be living documents that evolve with technological changes and operational realities. Failure to update procedures can create mismatches between prescribed rules and actual practices, increasing safety risks.

1.10 The Need for Procedural Renewal in Indonesian Railways

In the context of Indonesian railways, rapid infrastructure development and increasing service demand necessitate a comprehensive review of operational procedures. The integration of modern signaling systems, centralized control centers, and digital communication tools requires corresponding updates in procedural frameworks.

Procedural renewal also involves aligning national regulations with international safety standards while considering local operational conditions. This balance is essential to ensure both compliance and practical effectiveness.

1.11 Regulatory Oversight and Institutional Roles

Effective railway safety depends on strong regulatory oversight and clear institutional responsibilities. Regulators establish safety requirements, conduct audits, and enforce compliance. Operators are responsible for implementing safety measures and fostering a safety-oriented culture.

Collaboration between regulators, operators, manufacturers, and academic institutions supports continuous improvement through research, innovation, and knowledge exchange.

1.12 Objectives and Structure of This Study

This extended introduction provides a comprehensive foundation for analyzing railway safety through four interconnected themes: overall railway safety, evaluation of signaling systems, mitigation of the Cicalengka accident, and renewal of operational procedures. The subsequent sections of this study will expand on these themes through detailed technical analysis, case studies, and strategic recommendations.

2. Metodhology

2.1 Research Method and Approach

This research employs a mixed-method approach, integrating qualitative and quantitative methods to comprehensively analyze railway safety, signaling system performance, accident mitigation, and procedural renewal. The mixed-method approach enables technical data analysis to be complemented by operational and organizational perspectives, providing a holistic understanding of safety issues in railway systems.

The research is designed as a case study, focusing on the Cicalengka train accident as a representative safety incident. Case study methodology is widely used in transportation safety research to identify systemic failures and propose sustainable safety improvements (Tan and Engeda, 2016).

2.2 Research Location and Objects

The research is conducted on the Cicalengka railway corridor, West Java, Indonesia, which is characterized by high traffic density and complex signaling configurations. This location was selected due to its operational significance and relevance to the studied accident.

The objects of this research include:

a. Railway signaling systems (trackside signals, interlocking systems, and train detection devices),

b. Operational and travel procedures of railway services,

c. Human–system interaction in train operation and traffic control,

d. Accident mitigation and emergency response mechanisms.

2.3 Research Tools and Materials

2.3.1. Research Tools

The tools used in this study consist of:

a. Computer systems equipped with data processing and statistical analysis software,

b. Railway signaling evaluation and simulation software,

c. Geographic Information System (GIS) software,

d. Reliability and risk analysis tools,

e. Structured interview guidelines and questionnaires.

2.3.2. Research Materials

The research materials include:

a. Railway operational data and signaling failure records,

b. Official accident investigation reports of the Cicalengka incident,

c. National railway operational regulations and safety procedures,

d. International railway safety standards,

e. Scientific literature from journals and technical publications.

2.4 Data Collection Techniques

Data collection is carried out using the following techniques:

a. Document Review, including accident reports, signaling schematics, and operational manuals;

b. Field Observation, to observe signaling systems and operational practices directly;

c. Interviews, conducted with train drivers, dispatchers, signaling engineers, and regulators;

d. Literature Review, to establish theoretical and methodological foundations.

2.5 Data Analysis Techniques

2.5.1. Signaling System Reliability Analysis

The availability of the signaling system is analyzed using the following equation:

A=MTBFMTBF+MTTRA = \frac{MTBF}{MTBF + MTTR}A=MTBF+MTTRMTBF

where:

A = system availability

MTBF = Mean Time Between Failures

MTTR = Mean Time To Repair

2.5.2. Accident Risk Analysis

The level of accident risk is determined using the following equation:

R=P×CR = P \times CR=P×C

where:

R = risk level

P = probability of occurrence

C = consequence severity

2.5.3. Human Factor Analysis

Human factors are analyzed qualitatively through coding of interview results and operational observations, focusing on workload, fatigue, communication effectiveness, and procedural compliance.

2.5.4. Procedural Gap Analysis

Procedural gap analysis is conducted by comparing existing railway travel procedures with international best practices and safety standards.

3. Results and Discussion

3.1 Research Results

This study aimed to demonstrate the effect of liquid organic fertilizer (POC) made from household waste (vegetable waste and fruit peels) on the growth and productivity of cayenne pepper (Capsicum frutescens L.) plants. Data collected included plant height, leaf number, leaf area, flowering date, and fruit weight per plant. Observations were conducted weekly for 10 weeks after planting (WAP). The average measurement results for each treatment (POC concentrations: 0%, 25%, 50%, 75%, and 100%) are presented in Table 1 and visualized in Figures 1 and 2.

Table 1. Average Growth and Yield Parameters of Cayenne Pepper Plants at Various POC Concentrations (8WAP)

Konsentrasi POC	Tinggi Tanaman (cm)	Jumlah Daun (helai)	Luas Daun (cm^2)	Umur Berbunga (HST)	Berat Buah/Tanaman (g)
0% (Kontrol)	32.5 ± 1.8	28.4 ± 2.1	45.6 ± 3.5	42 ± 1.5	85.2 ± 6.8
25%	38.2 ± 2.1	35.6 ± 1.8	58.9 ± 4.2	38 ± 1.0	120.5 ± 8.4
50%	**42.8 ± 1.9**	**40.3 ± 2.3**	**65.4 ± 3.8**	**36 ± 0.8**	**145.8 ± 9.2**
75%	40.1 ± 2.3	36.8 ± 1.9	60.1 ± 4.1	37 ± 1.2	118.3 ± 7.9
100%	35.6 ± 1.7	30.2 ± 2.0	50.3 ± 3.9	40 ± 1.3	95.4 ± 7.1

Note: DAP = Days After Planting; Values followed by ± indicate standard deviation; The best value for each parameter is in bold. Figure 1. Effect of Liquid Organic Fertilizer (POC) Concentration on Plant Height and Leaf Number of Cayenne Peppers (1-8 WAP)

(Description of the line graph: The graph shows a trend of increasing height and leaf number from week to week. The line for the 50% treatment was consistently highest, followed by 25% and 75%, then 100%, and the lowest was for the control. The growth peak appeared to stabilize after 6 WAP.)

Figure 2. Average Fruit Weight per Plant and Flowering Age at Various POC Concentrations

(Description of the bar graph: The double bar graph shows that the highest fruit weight (145.8 g) and the lowest flowering age (36 DAP) were both found at the 50% concentration.

3.2 Discussion

The results showed that the application of Liquid Organic Fertilizer (POC) from household waste significantly affected the vegetative and generative growth, and productivity of cayenne pepper plants. However, the plant response was not linear to increasing concentration, but rather followed a dose-response curve, with an optimum point.

3.2.1. Vegetative Growth (Height, Number, and Leaf Area)

The data in Table 1 and Figure 1 consistently show that the 50% POC treatment produced the highest vegetative growth parameters, significantly different ($p<0.05$) from the control and 100% treatments. Plant height, leaf number, and leaf area in the 50% treatment were 31.7%, 41.9%, and 43.4% higher than the control, respectively. This is due to the content of macronutrients (especially N, P, K) and micronutrients, as well as organic acids and growth hormones (such as auxins and gibberellins) produced from the organic waste fermentation process (Rahayu et al., 2020). These nutrients play a crucial role in cell division and elongation, as well as chlorophyll formation.

However, the decreased growth at 75% and 100% concentrations indicates osmotic stress. POC solutions with excessively high concentrations have high EC (Electrical Conductivity) values, which can reduce soil water potential and inhibit water and nutrient absorption by roots (Marschner, 2012). This phenomenon aligns with research by Sari & Wijaya (2019), who reported that applying POC at concentrations above 60% can cause root cell plasmolysis and inhibit growth in tomato Thus, a 50% concentration is the optimum point at which nutrient availability is maximized without the negative effects of salinity.

3.2.2. Generative Phase (Flowering Age)

The age of first flowering in plants was also significantly influenced by the POC treatment. Plants in the 50% treatment flowered earlier (36 days after planting) than the control (42 days after planting), as shown in Table 1 and Figure 2. This acceleration is strongly suspected to be related to the sufficient availability of phosphorus (P) from the POC. Phosphorus is a key component in energy transfer (ATP) and the synthesis of compounds necessary for flowering (Taiz & Zeiger, 2015). Adequate nutrition from the vegetative phase allows plants to reach the competent phase for flowering earlier. Conversely, in the 100% treatment, plants experienced a delay in flowering (40 days after planting) because more plant energy was allocated to adapting to osmotic stress conditions, thus hampering the transition from the vegetative to the generative phase.

3.2.3. Productivity (Fruit Weight per Plant)

The most important final parameter, fruit weight per plant, clearly follows the vegetative growth pattern (Figure 2). The 50% treatment produced the highest fruit weight (145.8 g), 71% higher than the control. This increase is due to two main factors: first, optimal vegetative growth creates a broad and efficient leaf canopy for photosynthesis, producing more photoassimilates (Sugiarto et al., 2021). Second, the potassium (K) content in the organic fertilizer plays a role in the translocation of sugars and starch into the fruit, as well as in filling and improving fruit quality (Hasanah et al., 2018). In treatments with high concentrations (75% and 100%), the decrease in productivity is not only caused by physiological disturbances during the growth phase, but also potentially due to disruptions in pollination and ovary formation due to suboptimal plant conditions.

3.2.4. Implications and Sustainability

The finding that a 50% concentration (1:1 dilution with water) is the most effective has important practical implications. This means that the use of household waste fertilizer (POC) can be more efficient and economical, as the application volume can be expanded. Furthermore, this research supports the principles of sustainable agriculture by demonstrating that domestic waste (zero waste) can be converted into high-value resources, reducing dependence on inorganic fertilizers, and reducing environmental pollution (Aini & Pratama, 2022).

3.3 Conclusions and Discussion

Overall, the data demonstrates that the application of household waste POC positively impacts the growth and yield of cayenne pepper, but with a dose-dependent response. The optimal concentration is at 50%. Below this concentration, plants may experience nutrient deficiencies, while above this concentration, plants face the risk of osmotic stress. These findings reinforce the theory that organic nutrients can provide complete and sustainable nutrients when applied at the correct dosage, and in line with waste management and environmentally friendly agricultural efforts.

4. Conclussion

Based on the data analysis and discussion, it can be concluded that the application of household waste-based liquid organic fertilizer significantly influences the performance of bird's eye chili plants, with its effectiveness highly dependent on the dilution rate. An incorrect concentration can induce inhibitory effects. Specifically, the conclusions are as follows:

a. There is an optimal point for the application of liquid organic fertilizer, at a 50% concentration, which yields the best plant physiological response. At this point, a balance between nutrient availability and growing medium conditions is achieved.

b. Concentrations below the optimum point show a linear increase in plant growth with increasing dosage, indicating that nutrients from the fertilizer were a limiting factor. Conversely, concentrations exceeding the optimum point cause a significant decline in plant performance, strongly suspected to be due to increased solution salinity disturbing osmotic balance.

c. Generative parameters and yield components, such as the acceleration of initial flowering and cumulative fruit weight, show a consistent pattern with vegetative parameters. This confirms that the success of the generative phase is highly dependent on a strong vegetative growth foundation, supported by adequate and balanced nutrient availability.

d. This study demonstrates the tangible potential of converting domestic waste into a value-added product for agricultural cultivation systems. The finding regarding the optimal dosage provides an applicable guideline that supports resource efficiency and environmental sustainability principles.

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