

Institutional Gaps in PBBL Toll-Road Payment Oversight: Betung–Tempino–Jambi

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Abstract

Service-Based Periodic Payments (Pembayaran Berkala Berbasis Layanan, PBBL) for the Betung–Tempino–Jambi toll road create long-term government financial obligations requiring institutional oversight, service verification, and fiscal accountability. This study aimed to identify institutional weaknesses in PBBL payment supervision and formulate policy recommendations to strengthen governance and accountability. A qualitative policy analysis was conducted using regulatory documents, toll-road agreements, project information, and institutional developments. Priority issues were assessed through the Urgency, Seriousness, and Growth (USG) method, while underlying causes were examined using problem-tree analysis. Policy alternatives were evaluated through whole-of-government principles, principal–agent theory, the Three Lines Model, independent auditing, fiscal prudence, and state budget accountability frameworks. The findings identified annual PBBL obligations of approximately IDR 3.778 trillion over 15 years, with government payments separated from toll-revenue collection. The primary institutional challenge involved fragmented responsibilities across technical supervision, financing, and business operations. Furthermore, implementing regulations developed progressively after initial toll-road operations commenced, potentially creating weaknesses in service verification, independent auditing, and payment authorization. The study proposed six policy measures: clarifying institutional authority, verifying operational readiness before payment commencement, establishing integrated supervision and payment authorization, involving independent auditors, considering a transition toward a Public Service Agency (BLU) management model, and strengthening state budget accountability. These measures emphasize coordinated technical, fiscal, and operational controls supported by comprehensive regulations. The study concluded that integrated institutional oversight is essential for transparent, accountable, and sustainable PBBL implementation, although the proposed framework requires further empirical validation before its effectiveness can be established..



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INTRODUCTION

The development of the Trans-Sumatra Toll Road is part of a National Strategic Project assigned by the Indonesian government to PT Hutama Karya (Persero) under Presidential Regulation No. 100 of 2014, as most recently amended by Presidential Regulation No. 42 of 2024. This assignment was primarily motivated by the limited financial feasibility of several

toll-road sections in Sumatra, where projected toll revenues were insufficient to support full private-sector financing. Toll-road public–private partnership (PPP) projects in Indonesia are exposed to financing-structure, construction, operational-revenue, and regulatory risks, several of which have been documented on Trans-Sumatra sections in South Sumatra (Anggraini et al., 2026; Putri et al., 2023). During Phase II of the project, the government introduced an alternative investment return mechanism known as Service-Based Periodic Payments (Pembayaran Berkala Berbasis Layanan, PBBL). This mechanism follows the logic of availability payments, which the Indonesian government has increasingly adopted as an infrastructure financing option (Syugiarto, 2024). Minister of Finance Regulation No. 59 of 2023 provided the regulatory basis for implementing this mechanism across several Phase II toll-road sections, as stipulated in Article 4. The Betung (Sp. Sekayu)–Tempino–Jambi section was designated as the first Phase II section to be developed under the PBBL scheme.

Under conventional toll-road concession arrangements, Toll Road Business Entities (Badan Usaha Jalan Tol, BUJT) recover their investments through toll revenues collected during the concession period, thereby assuming substantial traffic demand and revenue risks. In contrast, the Betung–Tempino–Jambi section adopted a service-based payment mechanism under which the government provided quarterly payments to the BUJT over a 15-year period for each section, subject to compliance with Toll Road Performance Indicators (Indikator Kinerja Jalan Tol, IKJ). Under this arrangement, toll revenues were not retained by the BUJT but were deposited into the state treasury as Non-Tax State Revenue (Penerimaan Negara Bukan Pajak, PNBP). Consequently, the government's investment repayment obligations were financed through the State Revenue and Expenditure Budget (Anggaran Pendapatan dan Belanja Negara, APBN), with allocations administered through the Budget Implementation List (Daftar Isian Pelaksanaan Anggaran, DIPA) of the Ministry of Public Works. Transferring toll-collection responsibilities from toll-road business entities to the government alters the allocation of revenue risk and requires corresponding adjustments to concession arrangements (Parikesit et al., 2024). Studies of performance-based PPP payments further indicate that the share of payments linked to performance and the design of incentive coefficients determine whether such payments motivate service quality while protecting public resources (Cao et al., 2024; Su et al., 2023).

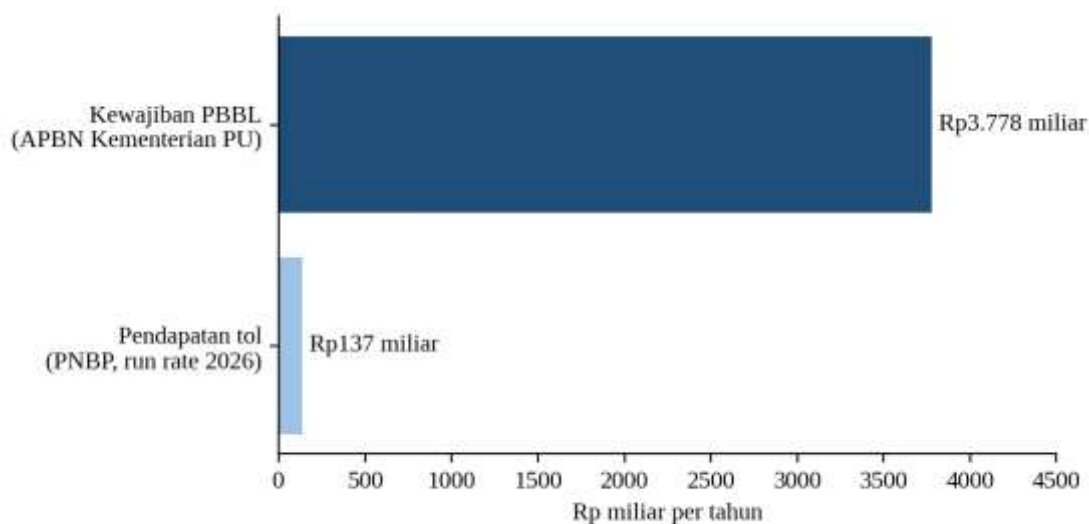
The Betung–Tempino–Jambi toll-road corridor extended approximately 170.73 km and comprised three sections. The annual PBBL obligation was established at IDR 3.778 trillion over 15 years, consisting of IDR 2.565 trillion for capital expenditure (CAPEX) and IDR 1.213 trillion for operating and maintenance expenditure (OPEX), as specified in the Minister of Public Works and Public Housing Letter No. BM 0701-Mn/331 of 2024. The financial allocation and characteristics of each section are presented in Table 1. Funding for the PBBL mechanism was allocated through the Ministry of Public Works' budget in accordance with Budget Allocation Document No. 05/BA/Dp/2024 and Article 9 of Minister of Finance Regulation No. 59 of 2023.

Table 1. Segment Profile and PBBL Value per Section

Section	Length	PBBL per year (IDR billion)	CAPEX	OPEX
Section 1: Betung–Tungkal Jaya	62.38 km	1.377	935	442
Section 2: Tungkal Jaya–Bayung Lencir	55.76 km	1.520	1.176	345
Section 3: Bayung Lencir–Simpang Ness*	52.59 km	881	455	426
Total	170.73 km	3.778	2.565	1.213

*Including the Bayung Lencir–Tempino Segment (34.10 km) whose construction is carried out by the Government. Source: Letter of the Minister of PUPR BM 0701-Mn/331 (2024); BA Business Plan 05/BA/Dp/2024.

The Betung–Tempino–Jambi Toll Road commenced operations in stages. The Bayung Lencir–Tempino segment became operational on October 16, 2024, pursuant to the Decree of the Minister of Public Works and Public Housing No. 2798/KPTS/M/2024, followed by the Tempino–Simpang Ness segment on September 4, 2025, under the Decree of the Minister of Public Works No. 813/KPTS/M/2025. Toll tariffs were established under Minister of Public Works Regulation No. 14 of 2026 and took effect on August 21, 2026. During the toll-free operating period, potential uncollected state revenue was estimated at IDR 216.66 billion as of February 2026 (BPJT, 2026). Following the implementation of toll tariffs, daily toll revenue was estimated at IDR 375–378 million, equivalent to approximately IDR 137 billion annually, or 3.6% of the annual Service-Based Periodic Payment (PBBL) obligation (PT Hutama Karya, 2024–2026). Figure 1 illustrates the comparison between the annual PBBL budget allocation and toll revenue classified as Non-Tax State Revenue (Penerimaan Negara Bukan Pajak, PNBP) for the Betung–Tempino–Jambi Toll Road.

**Figure 1.** PBBL Obligations and Toll Revenue per Year

Source: PUPR Minister Letter BM 0701-Mn/331 (2024); PT Hutama Karya data (2024–2026), processed.

The comparison indicated that toll revenue was insufficient to offset the budgetary obligations arising from the Service-Based Periodic Payment (PBBL) scheme. This fiscal

burden resulted from the financing arrangement established under the Toll Road Concession Agreement (Perjanjian Pengusahaan Jalan Tol, PPJT). Therefore, the primary concern was not merely the magnitude of the financial obligation but the effectiveness of controls governing each payment. Article 21 of Law No. 1 of 2004 concerning the State Treasury stipulates that payments charged to the State Revenue and Expenditure Budget (Anggaran Pendapatan dan Belanja Negara, APBN) must not be made before the corresponding goods or services have been received. Furthermore, Article 3(1) of Law No. 17 of 2003 concerning State Finance requires public financial management to be conducted in an orderly manner, in compliance with applicable regulations, and according to the principles of efficiency, transparency, and accountability. Budget transparency has been associated with stronger public financial sustainability (Cuadrado-Ballesteros & Bisogno, 2022), and effective government internal control systems have been shown to improve the quality of public financial management (Jurnalistiati & Maryani, 2025). Within the PBBL framework, verification of services received required reliable evidence that toll-road operations had satisfied the applicable Toll Road Performance Indicators (Indikator Kinerja Jalan Tol, IKJ), supported by independent inspections before payment authorization.

Effective payment control required supervisory and payment institutions to be fully operational from the commencement of toll-road services, with clearly defined responsibilities and authority. Evidence from PPP toll roads in Indonesia indicates that the quality of project governance significantly influences project performance (Nusriadi et al., 2024). As illustrated in Figure 2, the institutional framework governing PBBL oversight was established progressively after the relevant toll-road segment had commenced operations. The first PBBL payment claim was submitted on September 30, 2025, whereas the IKJ audit team was not established until October 22, 2025, and the paying agent was appointed subsequently. Arrangements for toll-revenue management and technical guidelines for Non-Tax State Revenue (Penerimaan Negara Bukan Pajak, PNBP) were introduced in August 2026. This sequence revealed a temporal mismatch between the commencement of payment-related obligations and the establishment of the necessary oversight mechanisms, indicating potential institutional weaknesses in service verification, audit readiness, and payment authorization.

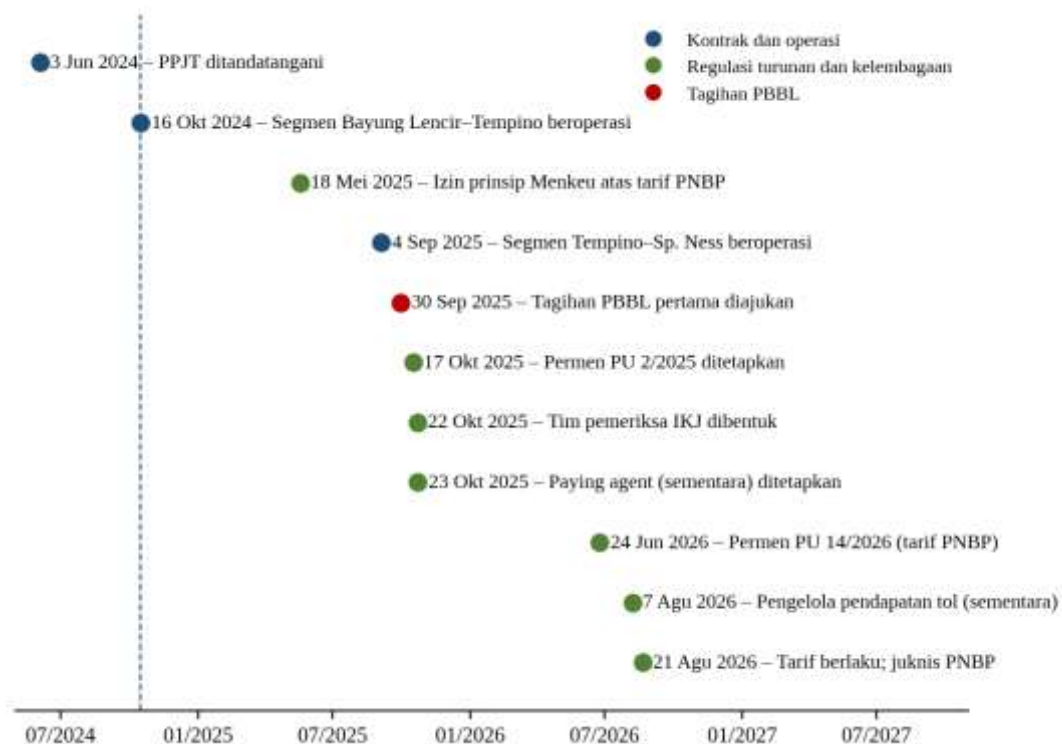


Figure 2. Chronology of Contracts, Operations, and Institutional Formation of the PBBL

Source: PPJT No. 01/2024; Ministry of Public Works and Public Works 2798/2024; Ministry of Public Works 813/2025; Decree of the Director General of Highways 92/2025; Decree of the Head of BPJT 04/2025; Ministerial Regulation of Public Works 2/2025; Ministerial Regulation of Public Works 14/2026; Ministry of Public Works 7431/2026; SE Director General of Highways 22/2026; BPJT (2025), processed.

The urgency of addressing these institutional weaknesses was further reinforced by two characteristics of the Service-Based Periodic Payment (PBBL) scheme. First, toll revenue was managed separately from PBBL payments, requiring all payment obligations to be subject to effective state budget expenditure controls. Second, PBBL commitments extended over a fixed 15-year period, whereas budget allocations were prepared and approved annually through the government budgeting process. These conditions heightened the fiscal implications of inadequate oversight, as errors in service verification or delays in payment could not be directly offset by toll revenue and could affect state budget management throughout the contractual period. Fragmented mandates across government units are a recurring obstacle to cross-sectoral coordination, which whole-of-government approaches seek to address (Aoki et al., 2024; Rukmana & Tamrin, 2024). Information asymmetry between governments and private operators can also reduce the efficiency of delegated infrastructure services unless monitoring and payment arrangements are carefully designed (Xiong, 2025), while internal audit units in Indonesian government institutions still require strengthening to perform their assurance roles under the Three Lines Model (Hasbara & Diyanty, 2023). Given the annual payment obligation of approximately IDR 3.78 trillion and the potential expansion of similar financing arrangements to other Phase II toll-road sections, strengthening institutional oversight of PBBL payments was essential to ensuring public expenditure accountability, adherence to good

corporate governance (GCG) principles, and prudent fiscal management. The key terms used in this study are summarized in Table 2.

Table 2. Key Terms

Terms	Definition
PBBL	Service-Based Periodic Payment; an investment return scheme in the form of periodic payments (<i>availability payment</i>) from the Government to BUJT for 15 years according to the fulfillment of the IKJ
BUJT	Toll Road Business Entities; in this section PT Hutama Karya (Persero) through the assignment of the Government
PPJT	Toll Road Concession Agreement between the Government and BUJT
IKJ	Toll road performance indicators that are the basis for PBBL payments and deductions
Toll PNBP	Toll tariff revenue paid to the state treasury as Non-Tax State Revenue
<i>Paying Agent</i>	Work unit that implements PBBL payments to BUJT

Source: PMK 59/2023; PPJT No. 01/2024; Ministerial Regulation of PU 14/2026.

Against this background, this policy paper addressed the significant oversight and fiscal accountability risks associated with Service-Based Periodic Payments (PBBL) for the Betung–Tempino–Jambi Toll Road, involving annual obligations of approximately IDR 3.78 trillion over 15 years, financed through the Ministry of Public Works' allocation under the State Revenue and Expenditure Budget (Anggaran Pendapatan dan Belanja Negara, APBN) (PMK 59/2023; BPJT, 2025). Specifically, this paper aimed to (1) identify the principal institutional weaknesses and underlying causes affecting PBBL payment oversight; (2) analyze potential solutions based on relevant governance theories, regulatory frameworks, and public financial management principles; and (3) formulate policy recommendations to strengthen institutional oversight, ensure accountability in state budget expenditures, promote adherence to good corporate governance (GCG) principles, and support prudent fiscal management.

METHOD

This policy paper employed a qualitative policy analysis approach using the Betung (Sp. Sekayu)–Tempino–Jambi Toll Road as a case study of the initial implementation of the Service-Based Periodic Payment (PBBL) scheme under Phase II of the Trans-Sumatra Toll Road project. Secondary data were collected from relevant laws and regulations, Toll Road Concession Agreement (Perjanjian Pengusahaan Jalan Tol, PPJT) No. 01 of 2024, ministerial decrees and official circulars, business planning records, PBBL valuation documents, Toll Road Regulatory Agency (Badan Pengatur Jalan Tol, BPJT) reports, and traffic volume and toll revenue data provided by PT Hutama Karya (Persero) for 2024–2026. The data were analyzed descriptively and supplemented by expert assessments to support the evaluation of policy alternatives. The analysis consisted of six stages.

First, issue identification and problem formulation were conducted by examining institutional weaknesses in PBBL payment oversight. Potential accountability gaps were identified by comparing existing payment control arrangements with the requirements established under applicable laws and regulations. The analysis drew on administrative records,

institutional timelines, and financial projections documented in the policy paper. The proposed institutional arrangements were evaluated conceptually rather than through empirical intervention testing. Accordingly, expert judgments and priority scores were treated as decision-support evidence rather than indicators of causal effectiveness.

Second, the primary problem was identified using the Urgency, Seriousness, and Growth (USG) prioritization method. Each identified problem was assessed on a five-point scale according to its urgency, potential consequences, and likelihood of escalation. The problem receiving the highest cumulative score was designated as the primary policy issue requiring intervention.

Third, the underlying causes of the primary problem were examined through a structured problem-tree analysis. Successive causal relationships were identified using iterative questioning to distinguish immediate causes from underlying institutional factors. The proposed relationships were reviewed for logical consistency, and the findings were consolidated into a problem statement describing the principal institutional weaknesses affecting PBBL payment oversight.

Fourth, potential policy solutions were analyzed using the whole-of-government approach, principal-agent theory, the Institute of Internal Auditors' Three Lines Model, independent verification principles for performance-based contracts, good governance, and fiscal prudence. These frameworks were examined alongside applicable regulatory provisions to identify potential improvements in institutional coordination, service verification, audit independence, and payment accountability. The resulting findings informed the development of alternative policy arrangements.

Fifth, policy alternatives were evaluated using criteria adapted from Bardach (2012), comprising technical feasibility, economic and financial feasibility, political viability, and administrative operability. A fifth criterion, state budget expenditure accountability, was incorporated to assess alignment with good corporate governance (GCG) principles and prudent public financial management. Each criterion was scored on a scale of 1–10 by four to five experts familiar with toll-road operations and public financial management. The assessment criteria are presented in Table 3.

Finally, policy recommendations were formulated based on the comparative assessment of the proposed alternatives. The highest-scoring alternatives were translated into recommendations specifying regulatory priorities, implementation stages, responsible institutions, and performance indicators. These recommendations were intended to strengthen institutional oversight, improve coordination among relevant authorities, and enhance accountability in PBBL payment administration.

Table 3. Alternative Assessment Criteria

Criteria	Assessment questions
<i>Technical feasibility</i>	Can alternatives be implemented with the available technical capacity, data, and legal basis?
<i>Economic and financial possibility</i>	Is the implementation cost reasonable compared to the benefits for payment control of Rp3.78 trillion per year?

Criteria	Assessment questions
<i>Political viability</i>	How likely are alternatives to gain the support of leaders and relevant stakeholders?
<i>Administrative operability</i>	Can the alternative be carried out with the existing authority and institutions without changes in high-level regulations?
State Budget Accountability (GCG and <i>prudent</i>)	How far do alternatives go ensuring every payment is verified, documented, auditable, and reported?

Source: adapted from Bardach (2012); KNKG (2021); IMF (2019).

RESULTS AND DISCUSSIONS

Identify Issues and Problems

The issue of high risk of controlling PBBL payments is reflected in three problems that are in different institutional dimensions.

1. The separation of toll revenue management from PBBL payments: toll revenue of around IDR 137 billion per year is paid into the state treasury as PNBP, while PBBL of IDR 3.78 trillion per year is paid from the Ministry of Public Works DIPA (PMK 59/2023; PU Ministerial Regulation 14/2026).
2. The division of PBBL management authority in the Ministry of Public Works according to technical functions, financing functions, and business functions located in different organizational units, with arrangements spread across four decisions from three different officials (Decree of the Minister of Public Works 2/2025; Decree of the Director General of Highways 92/2025; Decree of the Head of BPJT 04/2025; Decree of the Minister of Public Works 7431/2026; SE of the Director General of Highways 22/2026).
3. The difference between the horizon of PBBL obligations and the budget cycle: the obligation is fixed for 15 years, while the budget allocation is determined annually (PMK 59/2023 Articles 9–10).

The three problems each describe one dimension of payment control (Table 4). Problem 1 is on the budget allocation dimension, Problem 2 is on the authority dimension, and Problem 3 is on the budget cycle dimension.

Table 4. Three Problems on the Three Dimensions of Institutional Payment Control

	Issue 1	Issue 2	Issue 3
Dimensions	Budget allocation	Authority	Budget cycle
Influence on payment control	All PBBL burdens are controlled from the side of state budget spending, without balancing toll revenues	Control over checks and payments spread across multiple units	Control over payment certainty depends on the allocation each year

Source: author's analysis (2026).

To measure the accountability gap, the current conditions of payment control are compared with the standards set in laws and regulations (Table 5). These four standards are the benchmarks answered by the policy recommendations in subchapter 3.10.

Table 5. State Budget Payment Accountability Standards and Current Conditions

Standard	Basics	Conditions
Payment after verified service	UU 1/2004 Ps. 21; PPJT Ps. 15.3	The first bill will be entered on September 30, 2025, while the IKJ inspection team will be formed on October 22, 2025 (Decree of the Director General of Highways 92/2025; BPJT, 2025)
Separation of examiner, breaker, and payer functions	PP 60/2008	The IKJ audit team is entirely internal; independent auditors "can" be appointed
Orderly and responsible financial management	UU 17/2003 Ps. 3	<i>Paying agents</i> and toll revenue managers with temporary status
Effective IKJ monitoring system	PMK 59/2023 Ps. 5	PPJT supervision and IKJ supervision are on different lines of authority

Source: related laws and regulations; author's analysis (2026).

Determination of the Main Problem

The results of the assessment of the three problems with the USG (Urgency, Seriousness, Growth) scoring method are shown in Table 6.

Table 6. USG Scoring

Problem	Urgency	Seriousness	Growth	Total Score
Issue 1	4	4	4	12
Issue 2	5	5	5	15
Issue 3	4	5	5	14

Source: assessment results, processed by the author (2026).

Based on this assessment, Issue 2 obtained the highest score. The division of authority determines who ensures that each State Budget payment is valid and accountable, and this condition has already had an impact on current bills. This problem also has the potential to expand if the PBBL scheme is applied to other sections with the same institutional pattern. Thus, Issue 2 is designated as the main problem, while Issues 1 and 3 become part of the context and urgency as outlined in the Introduction.

Causes of Problems and Root Causes

Causes of Level 1 Problems

Why is the authority to manage PBBL divided?

- 2a. Each functional unit prepares PPJT derivative regulations partially after the section starts operating (Decree of the Director General of Highways 92/2025; Decree of the Head of BPJT 04/2025; Decree of the Minister of Public Works 7431/2026).
- 2b. Function *Paying Agent* and toll revenue managers are temporarily appointed in existing work units (Decree of the Head of BPJT 04/2025; Decree of the Ministry of Public Works 7431/2026).
- 2c. Derivative regulations require the approval of several ministries as well as separate internal decisions, including the appointment of independent auditors (PMK 59/2023; PP 44/2025; PPJT Article 9.8).

The three direct causes are complementary to each other. Cause 2a explains how derivative regulations are prepared, namely by each unit according to its authority and

gradually. Cause 2b explains the institutional status of payment implementers and revenue managers that are temporary. Cause 2c explains the dependence of the preparation of derivative regulations on cross-ministerial agreements and internal decisions.

Causes of Level 2 Problems

Why are the PPJT derivative regulations partially prepared after the section is operational?

- 2a1. The Betung–Tempino–Jambi section is the first section on the Trans Sumatra Toll Road Phase II to be undertaken under the PBBL scheme, so that the derivative regulations are prepared for the first time at the same time as the implementation of the agreement (PMK 59/2023 Article 4; PPJT No. 01/2024; BPJT, 2025).
- 2a2. Permen PU 2/2025 stipulated on October 17, 2025 regulates the division of business authority based on tariffs, without provisions for budgeting and PBBL payments, IKJ verification as a basis for deduction, and the management of toll PNBP (Permen PU 2/2025 Attachment C.3).
- 2a3. Permen PU 2/2025 places PPJT supervision on business function units, while supervision of PBBL IKJ is determined through the decision of the head of the technical function unit and reported to the head of the unit (Permen PU 2/2025 Appendix D; Decree of the Director General of Highways 92/2025).

Why were paying agents and toll revenue managers appointed on a temporary basis?

- 2b1. Work units in business function units receive tasks as *Paying Agent* PBBL until the toll road development fund management center was formed (Decree of the Head of BPJT 04/2025).
- 2b2. The toll revenue manager is appointed to the work unit of the national road implementation center in the section area until the fund management center is operational (Kepmen PU 7431/2026).
- 2b3. The BLU pattern toll road development fund management center is still in the process of being formed from October 2025 to August 2026 (BPJT, 2025; Kepmen PU 7431/2026).

Why do derivative regulations require cross-ministerial approval and internal decisions?

- 2v1. PMK 59/2023 stipulates the authority of PBBL at the Ministry of Public Works without appointing an implementing unit (PMK 59/2023 Article 17).
- 2c2. The toll tariff as PNBP is only being implemented for the first time, so it requires the principle permission of the Minister of Finance (May 2025) before the Ministerial Regulation on tariffs is set (June 2026) (PP 44/2025 Article 12; Permen PU 14/2026).
- 2v3. PPJT said that the Government "will appoint" an independent quality control consultant and "will compile" a supervisory structure without a deadline, and the decision to form a team stipulates that the consultant "may" be appointed as needed (PPJT Article 9.8.2–9.8.3; Decree of the Director General of Highways 92/2025 Sixth Dictum).

The relationship between the issue, the main problem, the level 1 cause, and the level 2 cause is depicted in the problem tree (Figure 3). The path in green shows the chain that leads to the root of the problem.

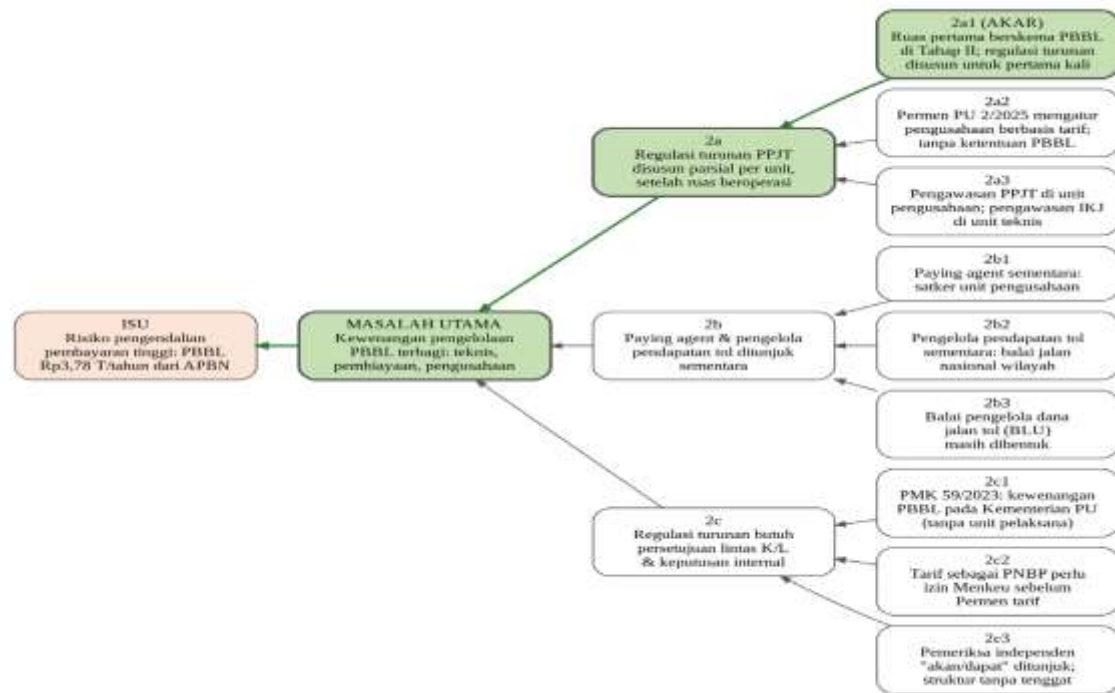


Figure 3. Problem Tree

Source: author's analysis (2026).

The causal chain is tested from two directions (Table 7), where each step is a logical consequence of the previous step and answers the question of "why" of the step above it.

Table 7. Causal Chain Logic Flow

Directions	Chain
Causes → consequences	The first section of the PBBL scheme in Phase II → derivative regulations were prepared for the first time at the same time as the implementation of the agreement → was partially prepared by each unit of function → PBBL management authority divided → high payment control risk
Consequences → causes	The risk of high payment control ← the authority is divided ← derivative regulations are partially prepared by each functional unit ← prepared for the first time at the same time as the implementation of the first segment of the agreement ← the PBBL scheme in Phase II

Source: author's analysis (2026).

Based on the search, the root of the problem is:

1. The Betung–Tempino–Jambi section is the first section on the Trans Sumatra Toll Road Phase II to be undertaken with the PBBL scheme, so that the derivative regulations are prepared for the first time at the same time as the implementation of the agreement (2a1);
2. PPJT derivative regulations are partially prepared by each functional unit after the segment operates (2a);
3. The management authority of PBBL is divided based on technical, financing, and business functions (Problem 2).

Problem Statement

With the logic (2a1) causing (2a) resulting in (Problem 2), the problem *statement* of this policy paper is formulated as follows: The first implementation of the PBBL scheme on the Trans Sumatra Toll Road Phase II on the Betung-Tempino-Jambi Section, with derivative regulations prepared for the first time at the same time as the implementation of the agreement, caused the PPJT derivative regulations to be prepared partially by each functional unit after the section was operational, resulting in the management authority of PBBL divided based on technical, financing, and business functions. This is what causes the high risk of controlling PBBL payments of Rp3.78 trillion per year which is fully paid from the State Budget of the Ministry of Public Works.

This problem statement is the starting point for the analysis of the direction of the solution in subchapters 3.5–3.7, the formulation and assessment of alternative policies in subchapters 3.8–3.9, and the policy recommendations in subchapter 3.10. The next discussion no longer focuses on the problem and its causes, but on the direction of the solution that can logically solve the problem statement by using the applicable theories, concepts, and regulations and policies as an analysis knife.

Analysis of Relevant Theories and Concepts

1. Whole-of-Government Approach

Christensen and Lægreid (2007) introduced the *whole-of-government approach* in response to the institutional fragmentation that arises when government tasks are divided into units that work according to their respective mandates. This approach emphasizes the integration of authority, horizontal coordination between units, and unity of purpose in the administration of a public affair. Integration does not always mean the merger of organizations. Integration can be achieved through a single framework of rules that defines the roles of each unit, the workflow between units, and clear points of accountability.

In the context of PBBL, this approach provides direction that technical, financing, and business functions do not have to be merged, but need to be tied in one instrument that regulates the PBBL cycle as a whole, starting from budgeting, IKJ audits, payment decisions, to toll revenue management. The instrument replaces the regulatory pattern spread across several separate decisions with a single reference that applies to all units involved.

2. Principal-Agent Theory

Jensen and Meckling (1976) describe the principal-agent relationship that arises when one party (principal) delegates work to another party (agent) who has more complete information about the execution of the work. Information asymmetry poses the risk that the agent does not act fully in accordance with the principal's interests. To reduce this risk, the principal needs monitoring mechanisms and incentive schemes that link rewards to verifiable performance.

In the PBBL scheme, the Government plays the role of the principal and the BUJT as the agent who controls information on the condition of toll road services. This theory provides a direction that payments must be based on performance verification carried

out before payment, with information generated by parties who have no direct interest in the results of verification. The readiness of the monitoring mechanism before the payment obligation runs is a prerequisite, not a complement.

3. Three-Line Model and Separation of Functions

The Institute of Internal Auditors (2020) formulated the Three-Line Model as a governance framework that separates three roles: the first line as the executor and risk owner, the second line as the controlling and monitoring function, and the third line as an independent assurance provider. This model is in line with Government Regulation Number 60 of 2008 concerning the Government Internal Control System which requires the separation of functions, authorization, and documentation of transactions as part of control activities.

This model provides the direction of the institutional arrangement of PBBL into three strict layers. The first layer is the IKJ auditor who assesses the fulfillment of services. The second layer is the unit that verifies, decides, and implements payments. The third layer is the Government Internal Supervision Apparatus (APIP) and the Financial and Development Supervisory Agency (BPKP) which provides assurance on the payment process. Each layer has different authorities and reporting channels, so that the auditor, decision-maker, and payer are not in one hand.

4. Independent Examiners in Performance-Based Contracts

The World Bank (2017) notes that service-based payment contracts generally place independent auditors, such as independent engineers or independent verifiers, to verify compliance with service standards before payment. Independent auditors are appointed from the beginning of the service life, work on an agreed framework of reference, and the results of their audits become the official basis for calculating payments and deductions.

This practice is relevant because the PPJT Betung-Tempino-Jambi Section Article 9.8 has mentioned the appointment of an independent quality control consultant. The resulting solution is to make the inspection by an independent auditor an obligation attached to every PBBL bill, with the appointment made before the determination of operations and contracts covering the entire payment period.

5. Principles of Good Governance

Komite Nasional Kebijakan Governansi (KNKG, 2021) establishes five principles of governance, namely transparency, accountability, responsibility, independence, and fairness. This principle is also a reference for SOE governance as the implementer of assignments. In PBBL payments, the five principles can be translated operationally: transparency through performance disclosure and payment; accountability through audit traces from the results of IKJ audits to payment orders; accountability through compliance with PPJT and regulations; independence through auditors who are separate from payers; and fairness through the consistent application of deductions.

The solution direction of this principle is the determination of measurable obligations for each principle, so that the fulfillment of GCG does not stop as a normative statement, but can be evaluated periodically.

6. Principles of Fiscal Prudence

The International Monetary Fund (2019) through the Fiscal Transparency Code emphasizes that the government's long-term obligations need to be identified, monitored, disclosed, and controlled periodically as part of prudent fiscal risk management. PBBL obligations are direct obligations that are fixed for 15 years. This principle provides direction for the need for periodic reporting on service performance, payment realization, and projected liabilities to fiscal managers, so that control does not only take place at the implementation level, but can also be monitored at the fiscal policy level.

Analysis of Applicable Regulations and Policies

The discussion of regulations and policies is aimed at identifying what has been regulated and the regulatory space that can still be filled to resolve the problem statement. Regulations are grouped into four groups.

1. State Financial Management and Internal Control

- a. Law Number 17 of 2003 concerning State Finance requires state finances to be managed in an orderly, compliant with regulations, efficient, economical, effective, transparent, and responsible (Article 3 paragraph 1).
- b. Law Number 1 of 2004 concerning the State Treasury emphasizes that payment of the State Budget expenses must not be made before goods and/or services are received (Article 21).
- c. Government Regulation Number 60 of 2008 concerning the Government Internal Control System requires the separation of functions, authorization, and transaction documentation.
- d. Presidential Regulation Number 192 of 2014 concerning BPKP provides internal supervision authority over state financial accountability.

This group of regulations provides accountability standards that must be met for every PBBL payment, but it is general. The available regulatory space is the translation of these standards into PBBL-specific procedures, for example the obligation of IKJ verification minutes as the basic document of each bill and the role of BPKP as an *assurance* provider in the payment cycle.

2. Toll Road Maintenance and PBBL Scheme

- a. Law Number 38 of 2004 concerning Roads as last amended by Law Number 6 of 2023 is the basis for the implementation and operation of toll roads.
- b. Government Regulation Number 23 of 2024 concerning Toll Roads regulates the determination of operations and tariffs by the Minister as well as toll revenue as PNPB if the return on SOE investment is sourced from the Government (Article 32).
- c. Presidential Regulation Number 100 of 2014 as last amended by Presidential Regulation Number 42 of 2024 became the basis for the PBBL scheme (Article 2F).
- d. Regulation of the Minister of Finance Number 59 of 2023 stipulates the objectives of optimizing the use value of the budget (Articles 2–3), the obligation of an

effective IKJ monitoring system in PPJT (Article 5), and the authority to plan to evaluate PBBL at the Ministry of Public Works (Article 17).

- e. PPJT Beras Betung (Sp. Sekayu)–Tempino–Jambi Number 01 of 2024 states that the Government will appoint an independent quality control consultant and develop an organizational structure and supervision mechanism (Article 9.8), and require payment no later than 14 working days from the date of the invoice being approved (Article 15.3).

This group places the authority of the PBBL in the Ministry of Public Works without appointing an implementing unit, so that the Minister of Public Works has room to determine the division of internal authority through ministerial regulations. PMK 59/2023 Article 5 and PPJT Article 9.8 have also provided the basis for the regulation of a more detailed independent monitoring and inspection system.

3. Authority and Institutions in the Ministry of Public Works

- a. Law Number 12 of 2011 as last amended by Law Number 13 of 2022 places ministerial regulations as binding laws and regulations.
- b. Regulation of the Minister of Public Works Number 2 of 2025 concerning the Implementation of Toll Road Implementation Authority divides the authority to regulate, coach, operate, and supervise toll roads in the Ministry of Public Works and becomes the official instrument for the division of authority for tariff-based business.
- c. Regulation of the Minister of Public Works Number 1 of 2024 concerning the Organization and Work Procedures of the Ministry of Public Works and the Regulation of the Minister of Public Works Number 1 of 2025 concerning the Organization and Work Procedures of the Technical Implementation Unit are the basis for the establishment of the technical implementation unit.
- d. Government Regulation Number 23 of 2005 as amended by Government Regulation Number 74 of 2012 concerning Financial Management of Public Service Agencies is the basis for fund management by the BLU pattern work unit.

This group points out that the instrument that binds all units in the Ministry of Public Works is a ministerial regulation, not a decision of the unit leader. Since the Minister of Public Works 2/2025 is focused on tariff-based business, special arrangements for PBBL can be pursued through amendments to the Ministerial Regulation or through a separate ministerial regulation with an equivalent position.

4. Toll PNB Management

- a. Government Regulation Number 44 of 2025 requires the approval of the head of the PNB management agency before the tariff is set (Article 12).
- b. Regulation of the Minister of Public Works Number 14 of 2026 regulates the collection, deposit, reconciliation, and reporting of toll revenue for the Betung-Tempino-Jambi section, and requires the PPJT to be adjusted no later than one year from the date of promulgation (Article 14).
- c. The Decree of the Minister of Public Works Number 7431 of 2026 and the SE of the Director General of Highways Number 22 of 2026 stipulate the temporary

management of toll revenue and technical instructions for collecting and depositing PNBP.

This group shows that the management of toll PNBP already has a regulatory basis, but it is determined separately from the PBBL payment arrangement. The obligation to adjust PPJT by July 2027 opens up momentum to harmonize the arrangement of receipts and payments in one governance framework.

Synthesis of Solution Directions

The theories, concepts, and regulations and policies discussed have resulted in several complementary solutions. The *whole-of-government approach* leads to a single instrument that governs the PBBL cycle as a whole. The principal-agent theory and practice of independent auditors lead to performance verification by independent parties before payment. The Three-Line Model and PP 60/2008 lead to the separation of the layers of auditors, decision-makers, and *insurers*. GCG principles and fiscal prudence lead to a track of audits, disclosures, and periodic reporting. Meanwhile, the applicable regulations show that the appropriate instrument to bind all units is a ministerial regulation, and there is a legal basis for institutions to remain in the BLU pattern. These relationships are summarized in Table 8.

Table 8. Theory, Regulation, and Solution Directions

Analysis knife	Solution direction	Resulting alternatives
<i>Whole-of-government</i> ; Law 12/2011; PU Ministerial Regulation 2/2025	Regulating the authority of PBBL in instruments that bind all units	Alt. 1 and Alt. 2
PP 23/2005 jo. PP 74/2012; PU Ministerial Regulation 1/2025	Permanent institutional for <i>paying agents</i> and fund managers	Alt. 3
<i>Whole-of-government</i> (horizontal coordination)	Guidelines for joint work between units	Alt. 4
PPJT Article 9.8; PMK 59/2023 Article 5	Certainty of the timing of the preparation of the supervision structure in the contract	Alt. 5
Principal-agent; independent inspector; three-line model	Mandatory independent auditors	Alt. 6
GCG; fiscal prudence; Law 17/2003; Law 1/2004	Audit track, disclosure, and reporting to fiscal managers	Assessment criteria and regulatory materials

Source: author's analysis (2026).

The principles of GCG and fiscal prudence are not used as separate alternatives, but are used as assessment criteria and mandatory materials for selected policies.

Policy Alternatives

Six alternatives were formulated to address the problem.

Alternative 1 amends PU Ministerial Regulation 2/2025 by adding a PBBL section to its authority matrix. This section would cover budgeting and payment, IKJ verification, and toll PNBP management. The option is consistent with the existing framework. However, the regulation was issued only in October 2025, and its matrix format was designed for tariff-based business. Amending it would reopen the whole matrix, and procedural material such as billing flows and audit trails does not fit a matrix format.

Alternative 2 establishes a separate ministerial regulation covering the entire PBBL cycle: division of authority, independent audit of IKJ, payment decisions, toll revenue management, and reporting. Like *Alternative 1*, it binds all units. Unlike *Alternative 1*, it complements Regulation 2/2025 rather than amending it, so it can contain detailed procedures and serve as a single reference for subsequent PBBL sections.

Alternative 3 accelerates the establishment of a BLU-pattern Toll Road Development Fund Management Center as a permanent paying agent and toll revenue manager. It ends the temporary status of both functions. However, it covers only part of the cycle and leaves the IKJ audit, the supervision line, and independent auditors unregulated.

Alternative 4 issues a ministerial circular as joint guidelines for inspection, decision, and payment. It is quick and practical. However, a circular is not a binding regulation under Law 12/2011, so it cannot determine the division of authority.

Alternative 5 amends the PPJT before the July 2027 adjustment deadline. The amendment would set deadlines for preparing the supervisory structure and appointing an independent auditor. It is contractually binding. However, it covers only one section and only the Government–BUJT relationship, not authority within the Ministry, and it requires both parties' agreement.

Alternative 6 mandates independent quality control consultants as IKJ inspectors under multi-year contracts. It strengthens the independence of inspection. However, it does not address the division of authority or toll revenue management, and it needs a regulatory basis of its own.

Table 9. Alternative Comparison to Problem Statements

Alternatives	Instruments	Coverage of the PBBL cycle	Addressing the root cause
Alt. 1	Amendment of ministerial regulation	Authority (matrix format)	Mostly
Alt. 2	New ministerial regulation	Authority, inspection, payment, revenue, reporting	Directly and fully
Alt. 3	Ministerial regulation on UPT organization	Payment and revenue	Partially
Alt. 4	Circular	Inter-unit coordination	Not normatively
Alt. 5	PPJT amendment	Contractual obligations, one section	Partially
Alt. 6	Consultant contracts	IKJ inspection	Partially

Source: author's analysis (2026).

Results of Policy Alternative Assessment

The six alternatives were assessed using the criteria in Table 3 (Table 10).

Table 10. Results of Policy Alternative Assessment

Alternatives	Technical feasibility	Economic and financial possibility	Political viability	Administrative operability	State Budget Accountability (GCG and prudent)	Total
Alternative 1	8	8	7	7	8	38

Alternatives	Technical feasibility	Economic and financial possibility	Political viability	Administrative operability	State Budget Accountability (GCG and prudent)	Total
Alternative 2	8	8	8	8	9	41
Alternative 3	6	7	7	6	7	33
Alternative 4	8	5	7	8	6	34
Alternative 5	7	6	6	6	6	31
Alternative 6	8	7	7	7	8	37

Source: assessment results, processed by the author (2026).

Alternative 2 scored highest (41).

5. **Technical and financial feasibility:** Alternatives 1 and 2 scored equally, since both use existing legal bases at low preparation cost.
6. **Political viability and administrative operability:** Alternative 2 scored higher because it does not reopen the newly issued authority matrix.
7. **Budget accountability:** Alternative 2 scored highest because it can contain detailed procedures that auditors can check, such as billing documents, verification trails, and reporting obligations.

Of the remaining alternatives, Alternative 6 is strong on accountability but limited to inspection. Alternative 4 is administratively easy but not binding. Alternatives 3 and 5 are partial and depend on processes outside the Minister's direct control.

Alternative 2 can also incorporate the substance of Alternatives 3–6 as its own provisions. It is therefore the recommended policy.

Policy Recommendations

It is recommended that the Minister of Public Works issue a Regulation on Supervision Governance and Service-Based Periodic Payments in Toll Road Business. The purpose is to reduce the risk in controlling PBBL payments, which are funded entirely by the Ministry's State Budget. The regulation implements the Ministry's authority under PMK 59/2023 Article 17. It complements Regulation 2/2025, which remains in force for tariff-based business. Its main provisions are listed in Table 11.

Table 11. Subject Matter of the Proposed Regulation

Material	Substance	Addresses
(a) Division of authority	Roles of the technical, financing, and business units in PBBL budgeting and payment, IKJ verification for deductions, and toll revenue (PNBP) management in one workflow	Main problem; 2a, 2a2
(b) Pre-operation readiness	Derivative regulations, paying agents, and inspection teams in place before each section begins operating	2a1, 2c3

Material	Substance	Addresses
(c) Single supervision line	PPJT supervision and IKJ supervision under one line of authority and reporting	2a3
(d) Independent oversight	Mandatory independent QC consultants as IKJ inspectors on multi-year contracts; APIP and BPKP as assurance providers	2v3; Table 5
(e) Institutional transition	Transfer of paying agent and toll revenue functions to the BLU-pattern fund management center, with a timeline	2b1–2b3
(f) Budget accountability	Audit trail per bill, quarterly reports to the Ministry of Finance, annual disclosure, GCG compliance evaluation	Issue; Table 5

Source: author's analysis (2026).

The business unit should draft the regulation jointly with the technical and financing units. The Legal Bureau should be involved, with coordination with the Ministry of Finance and BPKP. The timeline (Table 12) is aligned with the PPJT adjustment deadline of July 2027 under Regulation 14/2026.

Table 12. Implementation Stages

Time	Activities	Person in charge
Q4 2026	Drafting, based on evaluation of the Betung–Tempino–Jambi PBBL	Business, technical, and financing units
Q1 2027	Consultation with the Ministry of Finance and BPKP; harmonization	Legal Bureau; business unit
H1 2027	Issuance and promulgation; PPJT adjustment	Minister of Public Works
H2 2027	Application to Betung–Tempino–Jambi; appointment of independent inspectors	All related units
2028	First GCG evaluation; reference for other Phase II sections	Business unit; APIP

Source: author's analysis (2026).

Success is measured by four indicators:

1. Every PBBL bill carries IKJ verification minutes from an independent auditor before payment.
2. Paying agents and audit teams are appointed before the next section begins operating.
3. Performance and payment reports reach the Ministry of Finance every quarter.
4. There are no audit findings on the basis of PBBL payments.

CONCLUSION

The Service-Based Periodic Payment (PBBL) scheme places the responsibility for financing investment returns for the Betung–Tempino–Jambi Toll Road on the state budget, making payment accountability highly dependent on the institutional readiness, clarity of authority, and effectiveness of oversight mechanisms. The analysis revealed that the primary

challenge was not the magnitude of the fiscal obligation itself but the fragmented institutional governance framework, which developed progressively because this toll-road section represented the first implementation of the PBBL scheme under Phase II of the Trans-Sumatra Toll Road project. Consequently, implementing regulations derived from the Toll Road Concession Agreement (Perjanjian Pengusahaan Jalan Tol, PPJT) were developed separately by different functional units after the commencement of operations, resulting in fragmented responsibilities across technical supervision, financing, and business management. These institutional arrangements created potential weaknesses in coordination, service verification, and payment authorization, highlighting the need for a more integrated and clearly defined governance framework.

The theoretical, conceptual, and regulatory analysis indicated that the Ministry of Public Works had an established legal basis and institutional authority to develop an integrated PBBL governance framework applicable to all relevant organizational units. Such a framework would clarify institutional responsibilities, establish a clear separation of duties among verification, audit, payment authorization, and disbursement functions, and require independent verification and documented audit trails before payments were authorized. Among the six policy alternatives evaluated, establishing a dedicated Minister of Public Works Regulation on PBBL Oversight and Payment Governance received the highest assessment score and was identified as the most comprehensive proposed response to the institutional weaknesses. This regulatory approach could also provide a consistent governance reference for other toll-road sections adopting similar payment arrangements. Its implementation was expected to strengthen state budget expenditure accountability, promote adherence to good corporate governance (GCG) principles, and support prudent fiscal management. However, the effectiveness of the proposed framework would require further assessment following implementation.

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CONFLICT OF INTEREST

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AUTHOR CONTRIBUTION

All authors contributed to the preparation of this article. Alfi Hidayatul Rahmawati was responsible for the conceptualization of the study, data collection and analysis, interpretation of the results, and manuscript preparation. The other authors contributed to the review, editing, and final approval of the manuscript.

GENERATIVE ARTIFICIAL INTELLIGENCE USAGE STATEMENT

The authors declare that no generative artificial intelligence was used in the preparation of this article. (Sharonov, 2025)

REFERENCES

Anggraini, L., Bandu, J., Mulyati, A. S., & Farikhi, A. (2026). Stakeholder-based financial sustainability risk factors of toll road projects in Indonesia. *AGREGAT*, 11(1), 14572–

14580. <https://doi.org/10.30651/ag.v11i1.31427>
- Aoki, N., Tay, M., & Rawat, S. (2024). Whole-of-government and joined-up government: A systematic literature review. *Public Administration*, 102(2), 733–752. <https://doi.org/10.1111/padm.12949>
- Badan Pengatur Jalan Tol. (2025). *Overview perusahaan Jalan Tol Betung–Tempino–Jambi: PBBL, O&M, dan SK tarif* [Bahan paparan]. Kementerian Pekerjaan Umum.
- Badan Pengatur Jalan Tol. (2026). *Potensi kehilangan pendapatan Ruas Jalan Tol Betung (Sp. Sekayu)–Tempino–Jambi periode Oktober 2024–Februari 2026*. Kementerian Pekerjaan Umum.
- Bardach, E. (2012). *A practical guide for policy analysis: The eightfold path to more effective problem solving* (4th ed.). CQ Press.
- Cao, Y., Li, H., & Su, L. (2024). A dynamic performance-based payment mechanism for public-private partnership projects: An integrated model for principal-agent and multi-objective optimization models. *International Journal of Strategic Property Management*, 28(2), 116–129. <https://doi.org/10.3846/ijspm.2024.21183>
- Christensen, T., & Lægreid, P. (2007). The whole-of-government approach to public sector reform. *Public Administration Review*, 67(6), 1059–1066. <https://doi.org/10.1111/j.1540-6210.2007.00797.x>
- Cuadrado-Ballesteros, B., & Bisogno, M. (2022). Budget transparency and financial sustainability. *Journal of Public Budgeting, Accounting & Financial Management*, 34(6), 210–234. <https://doi.org/10.1108/JPBAFM-02-2022-0025>
- Hasbara, D. M., & Diyanty, V. (2023). Evaluasi peran inspektorat sebagai audit internal dalam three lines model. *AFRE (Accounting and Financial Review)*, 6(3), 316–329. <https://doi.org/10.26905/afr.v6i3.10333>
- International Monetary Fund. (2019). *Fiscal transparency code*. International Monetary Fund.
- Jensen, M. C., & Meckling, W. H. (1976). Theory of the firm: Managerial behavior, agency costs and ownership structure. *Journal of Financial Economics*, 3(4), 305–360. [https://doi.org/10.1016/0304-405X\(76\)90026-X](https://doi.org/10.1016/0304-405X(76)90026-X)
- Jurnalistiati, K. D., & Maryani, N. (2025). Pengaruh sistem pengendalian internal pemerintah terhadap pengelolaan keuangan daerah di Sekretariat DPRD Provinsi Jawa Barat. *COSTING: Journal of Economic, Business and Accounting*, 8(2), 1589–1602. <https://doi.org/10.31539/costing.v8i2.15031>
- Komite Nasional Kebijakan Governansi. (2021). *Pedoman umum governansi korporat Indonesia*.
- Nusriadi, L., Avianti, I., Tanzil, N. D., & Parikesit, D. (2024). The role of good project governance in PPP project for toll road infrastructure in Indonesia. *Journal of Infrastructure, Policy and Development*, 8(4), Article 3259. <https://doi.org/10.24294/jipd.v8i4.3259>
- Parikesit, D., Amalia, P., & Diyen, V. (2024). Regulatory challenges in modernizing toll road transaction systems in Indonesia. *Journal of Infrastructure, Policy and Development*, 8(8), Article 6341. <https://doi.org/10.24294/jipd.v8i8.6341>
- Perjanjian Perusahaan Jalan Tol Ruas Betung (Sp. Sekayu)–Tempino–Jambi Nomor 01 Tahun 2024.
- PT Utama Karya (Persero). (2024–2026). *Data lalu lintas dan pendapatan tol Ruas Betung–Tempino–Jambi* [Data internal].
- Putri, F. R., Susanti, B., & Toyfur, M. F. (2023). Critical risk analysis of toll road public-private partnership (PPP) project construction phase. *ASEAN Engineering Journal*, 13(3), 117–126. <https://doi.org/10.11113/aej.v13.19462>

- Rukmana, N. S., & Tamrin, S. H. (2024). Effectiveness of the whole-of-government approach in overcoming cross-sectoral problems in Makassar City. *Jurnal Ilmiah Ilmu Administrasi Publik*, 14(1), 65–72. <https://doi.org/10.26858/jiap.v14i1.62741>
- Su, L., Cao, Y., & Li, H. (2023). Performance-based payment structural design for infrastructure PPP projects. *International Journal of Strategic Property Management*, 27(2), 133–145. <https://doi.org/10.3846/ijspm.2023.19180>
- Syugiarto, S. (2024). Availability payment based public private partnerships in Indonesia. *PARADIGMA: Jurnal Administrasi Publik*, 3(1), 52–60. <https://doi.org/10.55100/paradigma.v3i1.63>
- The Institute of Internal Auditors. (2020). *The IIA's three lines model: An update of the three lines of defense*.
- World Bank. (2017). *Public-private partnerships reference guide* (Version 3).
- Xiong, M. (2025). Optimal governance for post-concession logistics infrastructure: A comparative study of self-operation vs. delegation under information asymmetry. *Sustainability*, 17(15), Article 6982. <https://doi.org/10.3390/su17156982>