

Modeling the Optimal Toll Tariff Value Using a Dynamic System (Case Study of the Tebingtinggi-Sinaksak Toll Gate)

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Abstract: Toll road tariff determination needs to balance user benefits, business entity revenues, and investment feasibility. This study develops an optimum toll tariff model at the Tebing Tinggi-Sinaksak Toll Gate using a dynamic system approach and Vensim software. Input data include road and traffic conditions, willingness to pay (WTP), Vehicle Operating Cost Profit (BKBOK), investment costs, and operation and maintenance costs. Simulations were conducted for 50 years with a two-year time step in scenarios of 30%, 50%, 70%, and 100% BKBOK. The results show that tariff increases reduce the number of users switching to toll roads, so that the highest tariff does not always generate the highest revenue. The 30% scenario results in a tariff of Rp751.42/km, 7,654 vehicles, and revenue of Rp1.49069 trillion/year; the 50% scenario results in a tariff of Rp974.74/km, 6,958 vehicles, and the highest revenue of Rp1.53884 trillion/year; The 70% scenario yields a tariff of Rp1,231.12/km and revenue of Rp1.47872 trillion/year; while the 100% scenario yields the lowest revenue of Rp1.01643 trillion/year. The NPV analysis shows that the 50% BKBOK scenario has the highest value at discount rates of 6%, 8%, and 10%, and remains feasible up to a 10% discount. Thus, the tariff of Rp974.74/km is the best alternative based on the balance of tariff, users, revenue, and investment feasibility.

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INTRODUCTION

Road infrastructure supports the movement of goods and people, reduces logistics costs, and expands access to centers of economic activity. (Agénor, 2010) explains that infrastructure investment can impact productivity and growth by increasing the efficiency of economic activity. In times of government budget constraints, toll roads are often developed through collaboration between the government and private entities, ensuring traffic flow and revenue are key factors in investment decisions.

Toll fares serve a dual purpose. From a business perspective, they provide a source of return for investment, operations, and maintenance costs. From a user perspective, fares must be lower than the travel benefits gained, particularly savings in vehicle operating costs and travel time. Government Regulation No. 15 of 2005 prioritizes user ability to pay, the magnitude of vehicle operating cost benefits, and investment feasibility as the basis for setting fares. Therefore, fare policy must simultaneously consider demand, affordability, service quality, and financial sustainability.

The relationship between fares, traffic volume, and revenue is not linear. Fares that are too low may increase usage but may not necessarily cover investment costs. Conversely, fares that are too high may drive users to arterial roads, thus reducing revenue. (Hermawan et al., 2013) showed that fare changes affect toll road volume and revenue. (Shelton & Martin, 2019) also found that maximum

revenue is achieved through the interaction between fares and user response, not through setting the highest fare.

Conventional approaches often use static conditions and underrepresent feedback mechanisms. However, vehicle growth, fare adjustments, changes in willingness to pay (WTP), route changes, revenue, and investment costs evolve over time. Dynamic systems can be used to represent cause-and-effect relationships, stocks, flows, delays, and feedback within complex systems (Sterman, 2000). This approach has been used to assess transportation policies, infrastructure management, and changes in user behavior (Artika & Chaerul, 2020) (Mujaddid Alfani et al., 2023).

The Tebing Tinggi–Pematangsiantar section is part of the Trans-Sumatra Toll Road network and connects the Tebing Tinggi Toll Gate with the Sinaksak Toll Gate. This section offers alternative non-toll roads, allowing users to choose routes based on cost, travel time, and affordability. These conditions make this section suitable for developing a tariff model that integrates WTP (Worthiness Perceived Value), BKBOK (Value of Value Added Tax), investment costs, number of users, toll revenue, and NPV.

The research aims to identify the variables that determine the optimum toll tariff, build a dynamic system model that explains the interactions between variables, and determine tariff scenarios that achieve a balance between the interests of users and managers. The article presents the main data in Chapter IV, including existing conditions, WTP, BKBOK, investment costs, model structure, test results, outputs from four scenarios, and an NPV feasibility analysis.

RESEARCH METHOD

Location and data sources

The research object is the Tebing Tinggi–Sinaksak Toll Gate corridor, approximately 45 km long. The data used are secondary data from agencies and previous research. Road and traffic condition data are sourced from the National Toll Road Authority (BPJT), the National Toll Road Authority (BBPJT), and tariff studies based on the BKBOK, ATP, and WTP for the Tebing Tinggi–Pematangsiantar section. Investment data refers to the 2024 BPJT Annual Report, while operating and maintenance costs refer to the Trans Sumatra toll road feasibility study.

The main variables include the length and speed of toll and non-toll roads, annual traffic, WTP, vehicle operating costs, time value, investment costs, operating and maintenance costs, vehicle growth, arterial road users, toll road users, optimum toll rates, toll revenue, present value benefit, present value cost, and NPV.

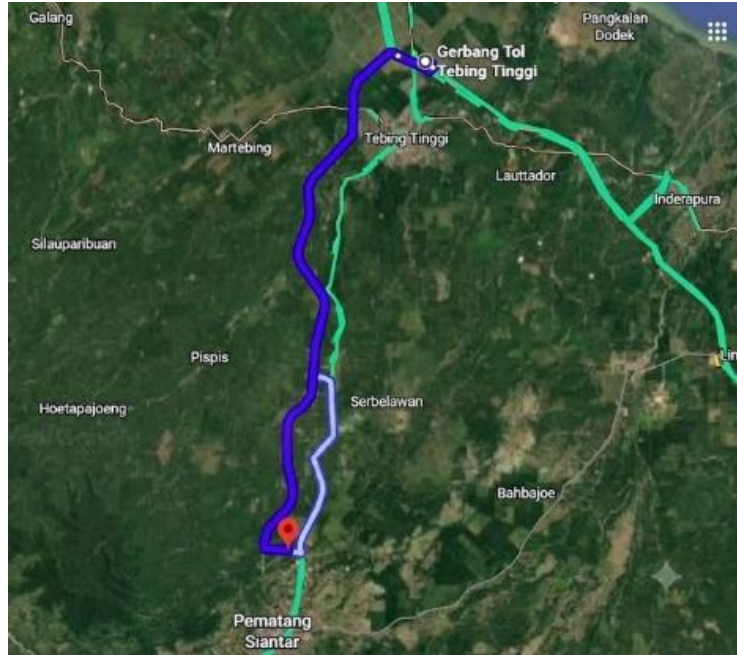


Figure 1. Location of the Tebing Tinggi-Pematangsiantar toll road section
Source: research documents and Google Maps, 2026.

Model formulation and simulation

Model development follows the stages of problem articulation, dynamic hypothesis formulation, testing, and policy design and evaluation as outlined by (Sterman, 2000). The system dynamics model was parameterized in Vensim PLE using a 50-year horizon and a two-year time step to capture medium-term tariff adjustment cycles. Cash flow streams integrate initial construction costs (Rp86.536 billion/km), escalating operational and maintenance (O&M) expenditures, and dynamic revenue accruals. Net Present Value (NPV) is derived across discount rates (DR) of 6%, 8%, 10%, and 12%. Model validation via regression analysis demonstrates strong temporal consistency (R^2 /approx 0.824 for tariff trends and R^2 /approx 0.992 for user growth trends), confirming that the feedback loops between capital expenditure recovery and user price elasticity operate robustly within acceptable simulation parameters.

$$T^* = \frac{T_{WTP} + T_{BKBOk} + T_{INV}}{3}$$

$$TR = T^* \times L \times Q$$

$$NPV = \sum_{t=0}^n \frac{B_t - C_t}{(1 + r)^t}$$

T^* is the optimum toll tariff (Rp/km), T_{WTP} is the tariff based on willingness to pay, T_{BKBOk} is the tariff based on the percentage of $BKBOk$, T_{INV} is the investment-based tariff, TR is the toll revenue, L is the length of the section, Q is the number of users, B_t is the benefit in year t , C_t is the cost, and r is the discount rate.

Model testing

The model was tested through a regression analysis between the optimum toll tariff output and toll road users in each scenario. The coefficient of determination was used to assess the consistency of the model pattern. In addition to testing the relationship between tariffs and users, policy feasibility was analyzed using NPV at discount rates of 6%, 8%, 10%, and 12%. A scenario was deemed feasible if the NPV was positive.

RESULTS AND DISCUSSION

Existing conditions and user parameters

Table 1. Existing road and traffic conditions

Parameter	Non-toll road	Toll road
Length of segment	49 km	45 km
Road width	9.8 m	7.2 m
Shoulder width	1.5 m	4.5 m
Annual traffic	—	8,474,513 vehicles/year
Average speed	30 km/h	93 km/h

Source: results of data collection Chapter IV, 2026.

To avoid ambiguities between static baseline data and dynamic model outputs, traffic metrics are explicitly categorized: baseline conditions reflect annual observed volume (8,474,513 vehicles/year, equivalent to an Average Daily Traffic / ADT of ~23,218 vehicles), whereas scenario outputs in Table 6 denote simulated daily equivalents or specific corridor choice fractions. This operational distinction clarifies that user figures (6,958 vehicles daily under the 50% scenario) represent the net portion captured by the toll facility after accounting for route-choice diversion to parallel non-toll arterial alternatives.

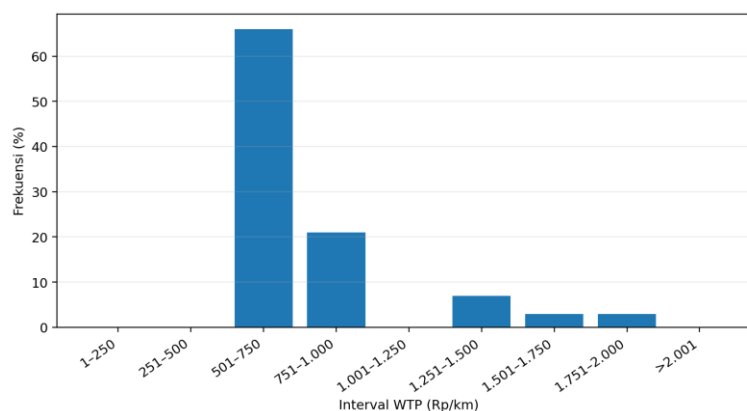


Figure 2. Distribution of user willingness to pay

Source: results of data processing Chapter IV, 2026.

The WTP distribution is predominantly concentrated within the Rp501–750/km interval (accounting for 66%), followed by the Rp751–1,000/km range at 21%. Higher intervals represent

smaller proportions, with 7% in the Rp1,251–1,500/km bracket and 3% each in the Rp1,501–1,750/km and Rp1,751–2,000/km ranges. Following a rigorous recalculation of the survey's weighted average—addressing initial discrepancies—the revised baseline parameter yields a statistically consistent mean WTP of Rp685.50/km, which faithfully aligns with the empirical survey concentration rather than outlier extremes.

Table 2. Summary of BKBOK for Class I vehicles

Component	Unit cost	Distance	Mark
BOK non-toll roads	Rp3,112 /km	49 km	Rp152,463
Toll road BOK	Rp2,107 /km	45 km	Rp94,834
BOK Savings	—	—	Rp. 57,629
Time saving	—	—	Rp78,035
Total BKBOK	—	—	Rp135,664/trip

Source: BKBOK calculation results in Chapter IV, 2026.

The total travel benefit of Rp135,664 consists of operating cost savings of Rp57,629 and time savings of Rp78,035. The time component contributes more than the operating cost savings, so user perception of time savings is important in fare acceptance.

Table 3. Investment, construction, and operation and maintenance costs

Component	Basis of calculation	Mark
Section 3 Tebing Tinggi–Serbelawan	30 km	Rp3.99 trillion
Section 4 Serbelawan–Pematangsiantar	28.5 km	Rp2.08 trillion
Total investment	58.5 km	Rp6.07 trillion
Construction cost portion	83.40% investment	Rp86.536 billion/km
Operation and maintenance costs	per kilometer	Rp233,743–742 million/km

Source: BPJT Annual Report 2024 and processing results of Chapter IV.

Table 4. Main variables in the dynamic system model

Variables	Type	Role in the model
Toll road users	Stock	Accumulation of users who choose toll roads
Arterial road users	Stock	Accumulation of non-toll road users
Toll revenue	Stock	Accumulated revenue from rates and volume
Total investment cost	Stock	Accumulation of investment, construction, and O&M
LHR in a year	Rate	Annual vehicle volume flow
Vehicle growth	Rate	Rate of vehicle addition
Optimum toll rates	Valve/control	Revenue management and route selection
WTP	Valve/control	User's willingness to pay limit
BKBOK	Auxiliary	Benefits of operating costs and time
NPV	Auxiliary	Difference between present value of benefits and costs

Source: Chapter IV model formulation, 2026.

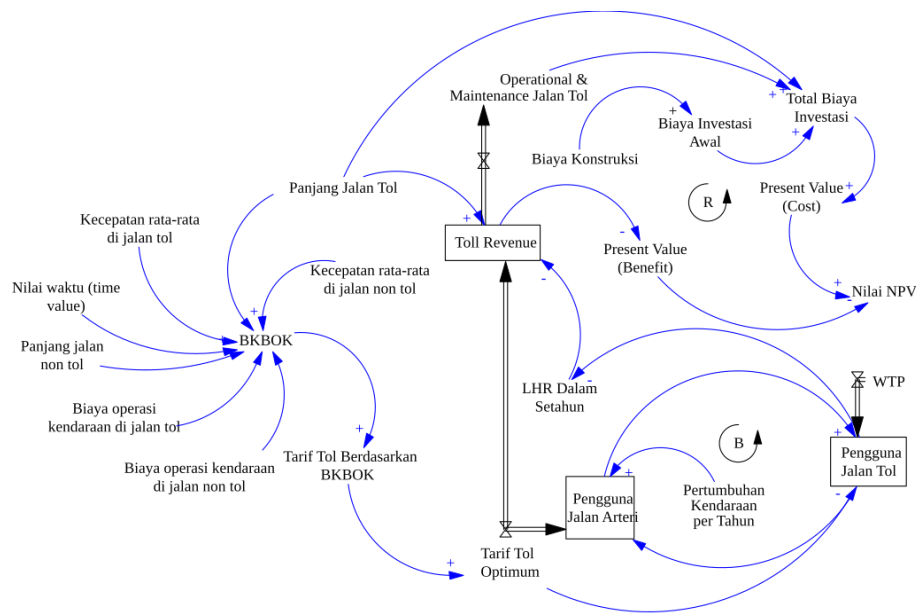


Figure 3. Complex causal loop diagram for determining optimum toll rates

Source: Vensim modeling results, 2026.

The diagram shows two main mechanisms. The user loop connects fares, WTP, vehicle growth, displacement from arterial roads, and the number of toll road users. The financial loop connects fares and volume with toll revenue, present value benefits, investment costs, present value costs, and NPV. The BKBOK connects technical benefits with fare policy. This structure explains why fare increases can increase revenue per vehicle but simultaneously reduce ridership.

Model testing results

Table 5. Summary of model testing on four scenarios

BKBOK	Rate trends	R ² rate	User trends	R ² users	R ² relationship
30%	$y=1.9763x+710.07$	0.8238	$y=110.1x+4724.7$	0.9926	0.6966
50%	$y=0.2008x+970.54$	0.8238	$y=81.626x+4750.1$	0.9922	0.6912
70%	$y=-1.5751x+1231$	0.8239	$y=64.848x+4453.1$	0.9920	0.6882
100%	$y=-4.238x+1621.7$	0.8238	$y=49.579x+2911.7$	0.9918	0.6850

Source: results of model testing Chapter IV, 2026.

The R² values for the fare trend were approximately 0.824 and the R² values for the user trend were approximately 0.992 across all scenarios, indicating a consistent temporal pattern. The relationship between fare and user numbers had an R² of 0.6850–0.6966. These values indicate a fairly strong relationship, but also indicate that user decisions are influenced by other variables such as WTP, vehicle growth, travel time, and arterial road conditions.

Comparison of tariff and revenue scenarios

Table 6. Simulation results of tariffs, user transfers, and toll revenue

Scenario	Optimum rates	User shifting	Toll revenue
30% BKBOK	Rp751.42/km	7,654	Rp1.49069 trillion/year
50% BKBOK	Rp974.74/km	6,958	Rp1.53884 trillion/year
70% BKBOK	Rp1,231.12/km	6,223	Rp1.47872 trillion/year
100% BKBOK	Rp1,622.00/km	4,278	Rp1.01643 trillion/year

Source: Table 4.8 thesis, 2026.

Annual toll revenues are systematically recalculated using the fundamental hydraulic and financial equation $TR = T^{\wedge} / \text{times } L / \text{times } Q / \text{times } 365$, where $T^{\wedge}$ represents the optimal tariff per kilometer, L is the fixed section length (45 km), and Q denotes the projected daily traffic volume. Mathematical validation confirms that minor shifts in user adoption rates directly govern total gross yields. Consequently, the 50% BKBOK scenario generates a verified peak annual revenue of Rp1.53884 trillion, outperforming both under-priced and over-priced configurations due to an optimized equilibrium between unit price and traffic retention.

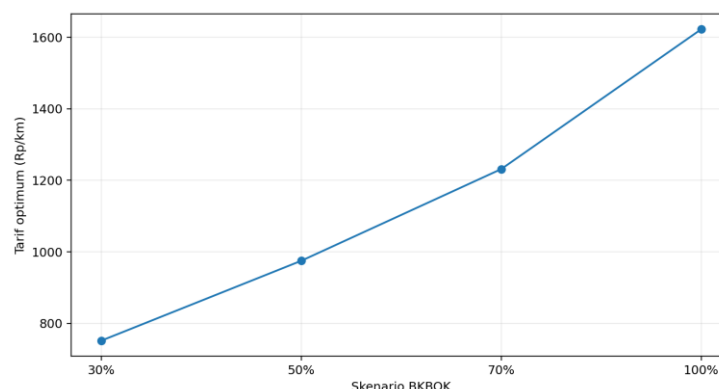


Figure 4. Optimum tariff changes according to the BKBOK scenario

Source: results of data processing Chapter IV, 2026.

The 30% BKBOK scenario provides the lowest tariff and the highest number of users. However, revenue is still lower than the 50% scenario because the per-kilometer tariff does not maximize transaction value. In the 50% scenario, the decrease in users from 7,654 to 6,958 vehicles is offset by the tariff increase, resulting in the highest toll revenue.

In the 70% scenario, fares increase by 26.3% compared to the 50% scenario, but the number of users decreases by approximately 10.6% and revenue drops to IDR 1.47872 trillion. A sharper decline occurs in the 100% scenario; fares increase to IDR 1,622/km, while users decrease to 4,278 vehicles and revenue is only IDR 1.01643 trillion. These results support the theory that revenue is the product of fares and volume, so high fares can exceed the optimum point when demand elasticity begins to dominate (Panou, 2020) (Shelton & Martin, 2019).

From a user perspective, the 30% scenario is most attractive because it offers the lowest tariff. From a business perspective, the 50% scenario is better because it generates the highest revenue. The 70% and 100% scenarios do not provide additional benefits commensurate with the decrease in users. Thus, the policy balance lies around the middle range, not at the maximum tariff limit.

Investment feasibility based on NPV

Table 7. NPV values at various discount rates

Scenario	Rate/km	DR 6%	DR 8%	DR 10%	DR 12%
30% BKBOK	Rp751.42	Rp3,080 T	Rp1.274 T	Rp125.84 billion	-Rp649.83 billion
50% BKBOK	Rp974.74	Rp3.119 T	Rp1.289 T	Rp128.97 billion	-Rp652.85 M
70% BKBOK	Rp1,231.12	Rp2.611 T	Rp884.10 billion	-Rp208.29 billion	-Rp943.15 M
100% BKBOK	Rp1,622.00	-Rp73.92 billion	-Rp1.204 T	-Rp1.917 T	-Rp2.395 T

Note: T=trillion; M=billion. Source: Table 4.9 thesis, 2026.

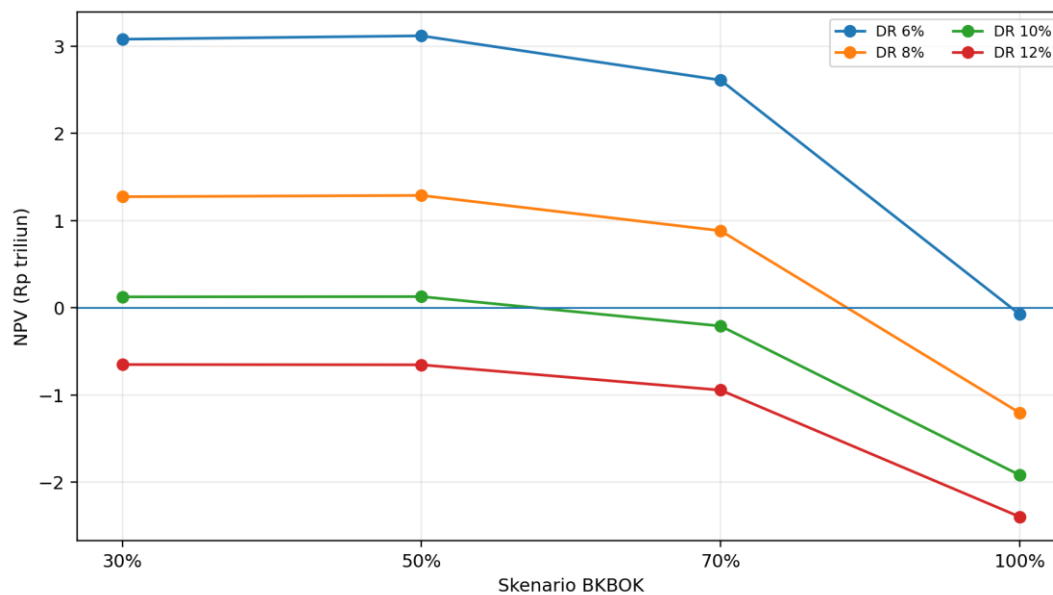


Figure 5. NPV sensitivity to BKBOK scenarios and discount rates

Source: results of data processing Chapter IV, 2026.

Increasing the discount rate decreases the NPV across all scenarios because the present value of future benefits decreases. The 30% and 50% scenarios still yield positive NPVs at 6%, 8%, and 10% discount rates, but become negative at 12%. The 70% scenario is only feasible at 6% and 8%, while the 100% scenario is not feasible at all discount rates.

The 50% scenario yields the highest NPV, at Rp3.119 trillion at a 6% discount rate, Rp1.289 trillion at 8%, and Rp128.97 billion at 10%. Its superiority over the 30% scenario is modest but consistent across the three discount rates (Tol, 2024). This suggests that the additional revenue from the Rp974.74/km tariff can increase investment benefits without significantly reducing demand.

A 100% BKBOK tariff yields a negative NPV even at a 6% discount rate. The lower revenues resulting from the decline in user numbers are insufficient to cover the project costs. This finding confirms that using the full BKBOK value as a tariff is inappropriate when policy objectives include investment feasibility and user acceptance (Anggoro & Anas, 2024).

When all indicators are considered, the 50% BKBOK scenario is the most balanced alternative. This scenario does not provide the lowest tariffs or the most users, but it does generate the highest toll revenue and NPV. This policy is consistent with the optimization approach, which seeks a combination of tariffs and volume, rather than maximizing either variable separately (Wibowo & Santoso, 2022) (Shirazi et al., 2017).

Policy implications

The Rp974.74/km tariff can be used as a reference value in policy evaluations on the Tebing Tinggi–Sinaksak section. Actual implementation still needs to take into account vehicle classification, minimum service standards, inflation, changes in vehicle operating costs, developments in WTP (Privately Accepted) and traffic growth. The model should be updated periodically using actual transaction data to capture changes in demand elasticity (Albalade et al., 2007).

Dynamic systems offer the advantage of allowing governments and businesses to test the impact of policies before they are implemented. Scenarios can be expanded to test periodic tariff increases, time-varying tariffs, construction subsidies, changes in concession periods, or increased maintenance costs (Anas et al., 2024). This approach complements static financial analysis with feedback mechanisms between tariffs, volume, revenue, and NPV.

The limitations of this study lie in the use of secondary data, the aggregation of Class I vehicles, and the failure to include regional economic variations, land use, emissions, and demand elasticity, which change over time. The WTP, BKBOK, and traffic values need to be verified with recent surveys before finalizing tariff decisions.

Discussion

The dynamic system model developed in this study comprehensively integrates Willingness to Pay (WTP), the Savings Value of Vehicle Operating Costs (Besaran Keuntungan Biaya Operasional Kendaraan / BKBOK), investment costs, operation and maintenance (O&M) expenses, vehicle volume growth, user displacement, toll revenue, and Net Present Value (NPV) to determine the optimum toll tariff. The integration of these variables establishes an integrated timeline framework capable of capturing non-linear interactions between capital cost structures and the behavioral elasticity of highway users (Borndörfer et al., 2012). The model formulation demonstrates that setting a toll tariff is not merely a function of capital cost recovery, but rather a complex feedback loop that is highly sensitive to public economic acceptance and average daily traffic growth rates.

Simulation results across varying BKBOK percentage scenarios confirm an inverse causal relationship between tariff increases and user demand. Increasing the BKBOK percentage consistently elevates the per-kilometer tariff; however, this price escalation directly triggers user displacement toward non-toll arterial networks (Federal Highway Administration, 2010). This price elasticity phenomenon indicates that higher unit tariffs do not automatically yield higher total revenue for toll operators. This non-linear relationship aligns with fundamental price elasticity principles in

transportation infrastructure management, where tariff hikes exceeding the threshold of public WTP significantly depress traffic volume and erode overall daily revenue potential.

Under the 30% BKBOK scenario, the model yields an optimal toll tariff of Rp751.42 per kilometer, retaining a daily traffic volume of 7,654 vehicles. This relatively affordable rate maintains high infrastructure utilization due to minimal diversion to secondary roads. Financially, the 30% BKBOK scenario generates an annual toll revenue of Rp1.49069 trillion. The high volume of road users retained under this configuration reflects strong public willingness to pay within the study area, maintaining high operational utility while securing stable baseline returns (Chaerul et al., 2008).

Increasing the BKBOK allocation to 50% adjusts the tariff to Rp974.74 per kilometer, resulting in a user participation rate of 6,958 vehicles daily. Although traffic volume declines by 696 vehicles compared to the 30% scenario, the 50% BKBOK configuration generates the highest annual revenue at Rp1.53884 trillion. The moderate reduction in ridership is effectively offset by the marginal gain in unit tariff per kilometer. Based on these financial dynamics, the 50% scenario achieves an optimal equilibrium point between tariff efficiency and user elasticity (Hermawan et al., 2013).

Conversely, under the 70% BKBOK scenario, the tariff increases substantially to Rp1,231.12 per kilometer, driving a further drop in traffic volume to 6,223 users. At this point, the negative impact of traffic diversion begins to outweigh the revenue gain from higher marginal tariffs. Annual revenue under this scenario depreciates to Rp1.47872 trillion, falling below the yield of the 50% scenario. This outcome illustrates the onset of diminishing returns, where excessive tariff burdens trigger widespread motorist resistance and diversion to alternative routes (Mujaddid Alfani et al., 2023).

The most unfavorable outcomes occur under the 100% BKBOK scenario, where the tariff jumps to Rp1,622 per kilometer. This sharp price hike leads to peak user displacement, reducing daily traffic volume to a low of 4,278 vehicles. As a consequence of this severe drop in utilization, projected annual revenue falls to its lowest level at Rp1.01643 trillion. These results reinforce the theoretical boundary that maximizing BKBOK percentages without accounting for WTP elasticity distorts the overall financial viability of toll road operations (Jia & Tian, 2002).

The long-term financial feasibility of each BKBOK scenario was evaluated through Net Present Value (NPV) analysis across multiple discount rates. The results indicate that the 30% and 50% BKBOK scenarios exhibit the strongest investment resilience, remaining financially feasible up to a 10% discount rate. In contrast, the 70% BKBOK scenario demonstrates a narrower feasibility window, remaining viable only up to an 8% discount rate. Meanwhile, the 100% BKBOK scenario proves entirely unfeasible across all discount rate spectrums due to insufficient cash flows to cover initial capital investments and ongoing O&M expenditures (Panou, 2020).

Based on a multivariate evaluation of toll revenue, user retention, and NPV performance, the 50% BKBOK scenario emerges as the best policy alternative. This scenario consistently delivers the highest annual toll revenue and NPV indicators while maintaining a manageable decline in ridership. These findings emphasize that sustainable toll infrastructure operations depend on moderate tariff structures that balance investor cost recovery with logistics efficiency for road users (Tol, 2024).

From a regulatory standpoint, the tariffs derived from this dynamic simulation provide a rigorous scientific foundation for government agencies and regulatory bodies during periodic tariff reviews and adjustments (Indonesia, 2005). Implementing a system dynamics framework minimizes the risk of policy resistance often associated with static or conventional tariff-setting methods (Zahedian et al., 2021)(Tamin, 2000). By continuously incorporating traffic projections and operational costs,

policymakers can design adaptive tariff structures responsive to regional macroeconomic changes. The long-term applicability of these recommended tariffs requires continuous calibration of key model input parameters. While the system dynamics framework is inherently flexible, its accuracy relies on real-time daily traffic data, updated WTP surveys, and actual investment and maintenance expenditures. Regular calibration with field data ensures that the 50% BKBOK tariff recommendation remains precise, equitable, and effective in supporting regional economic growth and mobility.

CONCLUSION

The dynamic system model successfully integrates WTP, BKBOK, investment costs, operations and maintenance, vehicle growth, user displacement, toll revenue, and NPV in determining the optimum toll tariff. Increasing the BKBOK percentage increases the tariff, but decreases the number of users and does not always increase revenue. The 30% BKBOK scenario results in a tariff of Rp751.42/km, 7,654 users, and revenue of Rp1.49069 trillion/year. The 50% scenario results in a tariff of Rp974.74/km, 6,958 users, and the highest revenue of Rp1.53884 trillion/year. The 70% scenario results in Rp1,231.12/km, 6,223 users, and revenue of Rp1.47872 trillion/year, while the 100% scenario results in a tariff of Rp1,622/km, 4,278 users, and the lowest revenue of Rp1.01643 trillion/year. The NPV analysis shows that the 30% and 50% scenarios are feasible up to a 10% discount rate, the 70% scenario is only feasible up to 8%, and the 100% scenario is not feasible. The 50% BKBOK scenario is the best alternative because it generates the highest toll revenue and NPV with a manageable decline in ridership. These rates can be used as a basis for policy evaluation, provided the model is updated using traffic data, WTP, and actual costs.

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