

Equilibrium Modeling for Optimizing Fuel Freight Distribution: The Case Study of the Cilacap-Bandung Energy Corridor, Indonesia

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ABSTRACT

Efficient and resilient fuel distribution systems are essential for ensuring the urban energy security, especially in developing regions that depend on road-based freight networks. This study models the distribution of fuel from the Cilacap oil refinery to Bandung, Indonesia — an essential corridor for the national energy supply. Using a gravity-based transportation demand model and an opportunity cost function, the study combines multiple regression analysis, trip generation modeling, and a four-step traffic assignment framework. The population, road conditions, fuel input and Gross Regional Domestic Product (GRDP) were analyzed to estimate the trip attractions, yielding an R^2 value of 0.957 and confirming the significant role of the infrastructure and socioeconomic factors in freight traffic behavior analysis. The simulation results showed that the existing network has problems, such as congestion and traffic load imbalances, but after optimizing the model, the traffic reduced from 10 to 5.1 vehicles per day and the Level of Service (LoS) improved from 0.85 to 0.49, providing practical solutions for infrastructure planning and policy development.

Keywords-freight transportation; traffic assignment; urban logistics; cilacap-bandung corridor; gravity model

I. INTRODUCTION

Fuel distribution is crucial in maintaining the energy stability, especially in cities with high energy demand, where the needs of industrial, transportation, and residential sectors are still growing [1-3]. The developed countries use pipeline networks connecting refineries to cities to ensure a stable and efficient fuel distribution [4, 5]. In contrast, many developing countries, such as Indonesia, still rely on the road-based fuel transportation from oil refineries, primarily using trucks [6-9], making the fuel distribution sensitive to the traffic conditions, road infrastructure, and transport efficiency [1, 10, 11]. According to the Indonesian Ministry of Transportation, the number of registered vehicles will have reached 168 million by 2025, with over 16.93 million in West Java alone [6]. From Cilacap, home to one of Indonesia's largest oil refineries, to Bandung, a major city on Java, a strategic route runs that is subject to the congestion and infrastructure limitations, creating

a threat to the urban energy stability [12-18]. Previous studies have examined general freight transportation systems and urban logistics, but they tend to generalize commodities [7, 8, 19-22]. Consequently, there is a significant research gap, as few studies have modeled the road-based fuel freight distribution, specifically as a strategic asset for the national energy security within a transportation equilibrium framework [13, 18]. The literature review revealed three findings: first, there is a persistent technological gap in fuel distribution systems between the developed and developing nations [1, 3, 5]; second, the rising vehicle ownership and worsening traffic congestion are putting acute pressure on road-based freight in Indonesia, leading to frequent delays and inefficiencies in the delivery of strategic commodities, including fuel [6, 9, 16]; third, although the urban freight has been extensively studied, most research generalizes across commodity types, overlooking the unique logistical and strategic challenges associated with the fuel transport and its central role in the national energy

security [7, 18, 23]. This study proposes a modeling approach that explicitly links the fuel freight distribution with the energy resilience outcomes. The objective of this study was to develop an effective and efficient fuel distribution model from oil refineries to urban areas, using the Cilacap–Bandung corridor as a case study. The proposed model intends to improve the design of energy distribution systems that are more durable and adaptable, capable of handling the increased transportation demands while ensuring the urban energy security. Three primary research questions guided the investigation: 1) What are the most influential factors affecting the fuel freight flows along the Cilacap–Bandung corridor? 2) How can a gravity-based model be calibrated to accurately simulate the current distribution networks? 3) To what extent can the network performance be improved through traffic assignment optimizations?

Based on these questions, the study hypothesizes that optimizing the freight distribution system using data can significantly improve the LoS, reduce congestion, and strengthen the resilience of the regional fuel supply chain. Consequently, it applies a gravity-based transportation equilibrium model, which is typically used for general passenger or freight traffic, to address the specific strategic challenge of fuel distribution. The current work provides the first detailed model of the critical Cilacap–Bandung energy corridor in Indonesia, offering empirical data and analysis of a vital, yet, understudied route, while it provides a quantitative framework to assess and enhance the urban energy resilience from a logistics perspective.

II. METHODOLOGY

A. Research Design

This study uses a quantitative approach to model the demand for fuel transportation from the Cilacap oil refinery to urban areas, especially Bandung, by analyzing the effectiveness and efficiency of the freight traffic systems in maintaining the city energy supply.

B. Variables

The dependent variable is the fuel freight transportation traffic volume, including urban population, GRDP, and spatial interaction between zones. These variables were used to develop a simulation model based on the traffic flow and commodity movement patterns [18].

C. Sampling and Research Area

The present study focuses on a critical distribution corridor, the Cilacap–Bandung route, as shown in Figure 1, which is of strategic importance in supplying fuel to the urban Bandung area. The selection of the sampling zones was determined by several factors, including administrative boundaries, the accessibility of the road network, and the intensity of freight transportation. The research area for this study consists of key transportation corridors that traverse multiple administrative regions, namely Bandung (BDG), Garut (GRT), Tasikmalaya Regency (TSR), Tasikmalaya City (TSC), Ciamis (CAS), Banjar (BJR), and Cilacap (CAP). These regions are interconnected by a primary route along which survey data

were collected. The location map illustrates the primary links and survey points used in the present analysis.

D. Data Collection

The primary data for this study were obtained from manual traffic counting surveys, which were conducted by trained researchers over the following periods of peak traffic: 07:00–09:00, 16:00–18:00, on Tuesday, Wednesday, and Thursday in June 2024. The number of vehicles was recorded and classified by type to identify the heavy freight trucks assumed to be carrying fuel based on their typical size and tanker configuration.

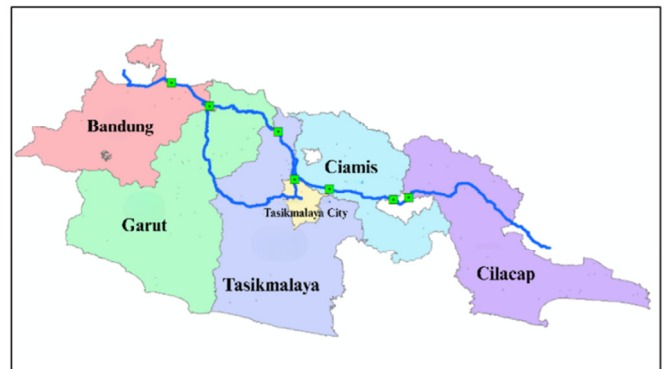


Fig. 1. Map of the Cilacap–Bandung fuel distribution corridor showing the key zones (CAP, BJR, CAS, TSC, TSR, GRT, and BDG) and survey locations.

The direct observation method was selected to obtain actual traffic flow data [24]. The data were supplemented by secondary data on population, GRDP, and road network characteristics obtained from the Indonesian Central Statistics Agency (BPS) and the Ministry of Public Works, respectively. The selection of the sampling locations was based on the objective of capturing the traffic entering and exiting the major administrative zones along the designated corridor.

E. Data Analysis

The transportation demand model used in this study follows a four-step framework, incorporating a gravity-based opportunity model [25–27]. The approach is initiated with the estimation of the aggregate commodity flows between the specified origin and destination zones. The total flow for all commodity types is calculated by summing the flows for each commodity across the same origin-destination pair as:

$$V_l^m = \sum_{i=1}^N \sum_{d=1}^N T_{id}^m \cdot p_{id}^{lm} \quad (1)$$

where (V_l^m) is the traffic volume on link (l) for commodity (m) , (T_{id}^m) is the flow from zone (i) to (d) , and (p_{id}^{lm}) is the proportion of that flow using link (l) . To estimate the individual commodity flows, the gravity opportunity model is applied:

$$T_{id} = k \frac{O_i \cdot D_d}{a_{id}^2} \quad (2)$$

This model considers the trip production potential at the origin (O_i) , attraction strength at the destination (D_d) , and impedance between the zones, which is a function of the

distance (d_{id}). The balancing factors A_i and B_d are iteratively computed to ensure that the estimated flows match the known totals of trip productions and attractions:

$$A_i^m = [\sum(B_d^m \cdot D_d^m \cdot f_{id}^m)]^{-1} \tag{3}$$

$$B_d^m = [\sum(A_i^m \cdot O_i^m \cdot f_{id}^m)]^{-1} \tag{4}$$

where f_{id}^m represents the impedance (or friction) function between the zones (i) and (d) for commodity (m). The traffic volume on each link is then determined by allocating these flows across the network using a specific path or link allocation proportion. This approach is intended to address the dynamics of commodity movements within the transportation network, thereby ensuring a balanced flow of goods across designated zones. A basic gravity model is employed to provide a generalized representation of the flow distribution. This model links the volume of trips to the product of trip generation and attraction, which is inversely proportional to the square of the distance between the zones:

$$T_{id}^k = T_{id} \frac{\exp(-\beta \cdot c_{id}^k)}{\sum_{m=1}^M \exp(-\beta \cdot c_{id}^m)} \tag{5}$$

The mode selection is analyzed using a multinomial logit model, which calculates the probability of selecting a given mode based on the generalized cost associated with each travel mode. This probabilistic approach enables a more realistic depiction of the traveler behavior within multimodal transportation networks. The final traffic simulation includes all components—commodity flows, mode shares, cost functions, and path allocation—to estimate the traffic volumes on each link under the specified infrastructure conditions. This integrative approach furnishes exhaustive insights into the traffic behavior, hence providing a more thorough foundation for informed transportation-planning decisions:

$$V_i^k = \sum_{d=1}^N \sum_{l=1}^N \left[O_i^k D_d^k A_i^k B_d^k f_{id}^k P_{id}^{ik} \frac{\exp(-\beta c_{id}^k)}{\sum_{m=1}^M \exp(-\beta c_{id}^m)} \right] \tag{6}$$

The transportation model was estimated using the least-squares method, a technique that seeks to minimize the discrepancy between the observed and estimated traffic flows. The objective function calculates the sum of the squared relative errors across all links:

$$S = \sum_{l=1}^L \left[\frac{(V_l - v_l)}{v_l} \right]^2 \tag{7}$$

In order to estimate the key model parameter β , which influences the sensitivity to cost in the mode choice model, the Newton-Raphson method is utilized in conjunction with Gaussian elimination. This approach involves refining the parameter values through iterative processes until an optimal match is achieved between the observed and estimated traffic flows, thus ensuring the validity and predictive accuracy of the model:

$$f(\beta_0 + h) = f(\beta_0) + \frac{\partial f}{\partial \beta} \cdot \beta \tag{8}$$

F. Research Procedure

The study's methodology followed a structured sequence of data collection, designed to capture metrics, such as traffic volumes and other variables that influence the travel behavior, as depicted in Figure 2. A linear regression analysis followed to ascertain the correlation between the independent variables and traffic volumes, including a range of statistical assessments, t-tests, F-tests, and R^2 analysis. Subsequently, a trip generation model was developed to estimate the number of trips made to each zone. These estimates form the basis for constructing an Origin-Destination Matrix (ODM), which presents the expected trip interactions between the zones. The ODM is iteratively balanced to ensure that the total trip production and attraction are consistent across all zones. In the event that the matrix fails to converge, the balancing process is repeated with the adjusted parameters until a stable distribution is achieved [18, 26].

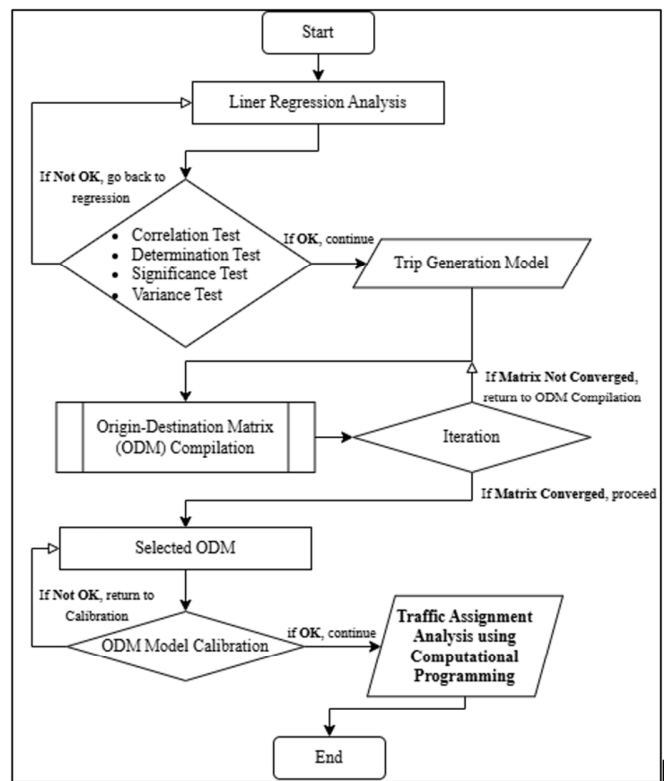


Fig. 2. Methodological flowchart showing the sequential process of data collection, modeling, calibration, and simulation.

In order to achieve stability, the model calibration was carried out by adjusting the parameters so that the simulated link volumes aligned with the observed traffic data. The model's validation was determined by the calibration errors falling within acceptable limits. Finally, the traffic assignment was simulated using computational tools to model the interzonal movements and assess the performance of the existing infrastructure. These results inform the future planning and highlight potential areas for network improvement.

III. RESULTS AND DISCUSSION

A. Trip Attraction Modeling

The objective of this study was to ascertain which variables exert the most significant influence on the flow of freight trucks into urban areas. The dependent variable in the analysis was the number of freight trucks entering a given area, measured in vehicles per day. The independent variables were the fuel input (in tons), total population, total length of roads in good and fair condition (in km), GRDP (in trillion Indonesian Rupiah), and the number of registered vehicles. The model that combined the fuel input, population, and road length exhibited the best performance among those tested, having a high R^2 value of 0.957 and an adjusted R^2 of 0.913, while also passing both the F-test and the T-test for statistical significance. Consequently, it was selected as the most appropriate model for estimating the trip attraction in the freight transportation context. A series of regression models were evaluated, incorporating diverse variable combinations. The results of this process are presented in Table I, showing the coefficient of determination (R^2), the adjusted R^2 , and the outcomes of the F- and T-statistical tests for each model configuration.

TABLE I. SUMMARY OF LINEAR REGRESSION OUTPUT

D variable	I variables	R^2	Adj R^2	F Test	T Test
Y	X_1, X_2, X_3, X_4, X_5	0.983	0.900	✘	✘
Y	X_1, X_2, X_3	0.957	0.913	✓	✓
Y	X_1, X_2	0.889	0.834	✓	✘
Y	X_2, X_3, X_4	0.857	0.871	✓	✘

Consequently, it was selected as the most appropriate model for estimating the trip attraction in the freight transportation context. The resulting regression equation, expressed in logarithmic form to enhance the linearity and minimize heteroscedasticity, is:

$$\ln Y = -2.7 - 2(\ln X_1) + 1.6(\ln X_2) + 0.9(\ln X_3) \quad (9)$$

where Y is the estimated number of incoming freight trucks per day, X_1 is the fuel input in tons, X_2 is the population, and X_3 is the length of roads in good and fair condition in km. The negative coefficient for the fuel input suggests that a higher volume of fuel supplied may be associated with lower truck inflows, possibly because of greater delivery efficiency or centralized storage. Conversely, the population size and the quality of road infrastructure exhibited a positive correlation with the freight traffic. This suggests that regions with larger populations and more advanced road networks are more likely to experience higher levels of freight movement. This model provides a statistically reliable foundation for estimating the freight trip attractions in the subsequent stages of the transportation demand modeling process [9, 27, 28]. The regression model was subjected to further evaluation to ascertain the assumption of normality of the residuals. Two diagnostic plots were used to assess this: the histogram of standardized residuals, as illustrated in Figure 3, and the normal Probability-Probability (P-P) plot.

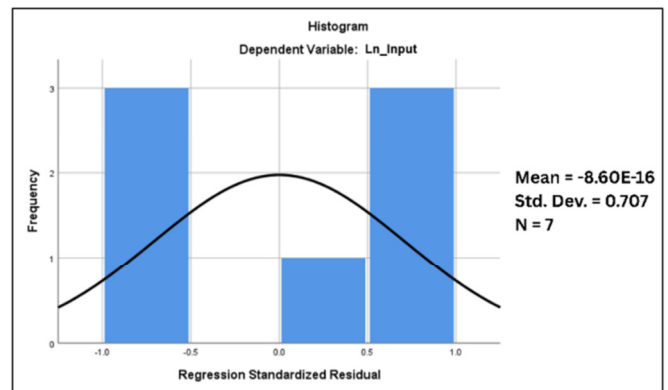


Fig. 3. Histogram of the standardized residuals from the regression model, demonstrating the approximate normality of the error distribution.

The statistical analysis revealed that the residuals exhibited a relatively symmetrical distribution around the mean, which was approximately zero, with a standard deviation of 0.707. The bell-shaped curve indicates a pattern that is generally consistent with a normal distribution. In addition, the P-P plot in Figure 4 compares the observed cumulative probabilities of the standardized residuals with the expected values under a normal distribution.

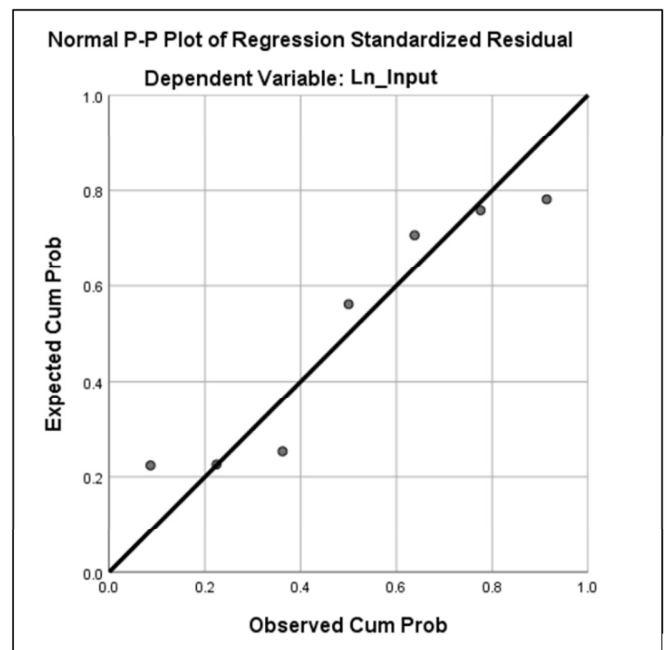


Fig. 4. P-P plot of the standardized residuals. The points lie close to the diagonal, indicating a normal distribution and regression validity.

The statistical analysis indicates that the points are located in close proximity to the diagonal reference line, thereby suggesting that the residuals approximate a normal distribution. This finding lends credence to the regression model, particularly with respect to the underlying assumptions concerning the distribution of error terms. These diagnostic plots confirm that the residuals do not deviate significantly

from a normal distribution, thus reinforcing the reliability and robustness of the regression model used for trip attraction analysis [17, 22].

B. Trip Distribution

The regression model developed in SPSS was used to derive the impedance coefficients for the trip-distribution stage. These coefficients form the basis for constructing the gravitation-based modeling approach's impedance function [17], as presented in Table II. The statistically significant β coefficient confirms the efficacy of this function in the gravity model for accounting for resistance between the zone pairs. The impedance function parameters are determined to be $\alpha = 15.843$ and $\beta = 2.094 \times 10^{-7}$. The negative exponential impedance function is:

$$f(C_{id}) = e^{-\beta C_{id}} \tag{10}$$

The impedance matrix between the zones was then calculated based on this function, as presented in Table III, demonstrating that the zones with closer proximity (CAP-BJR, 0.729) experience lower resistance, while longer-distance pairs, like CAP-BDG (0.440) have higher impedance. The model calculates the final trip distribution matrix employing the Attraction-Constrained Gravity Regression (ACGR) approach. In this model, the trip attraction values are known and fixed, whereas the balancing factor A_i is assumed to be 1 and balancing factor B_d is computed to ensure stability in the distribution, as exhibited in Table IV.

TABLE II. IMPEDANCE COEFFICIENTS

Model	Unstandardized coefficients	Standardized coefficients		T	Sig.	
	B	Std. error	Beta			
1	(Constant)	15.843	0.168		94.373	0.000
	VAR00002	2.094E-7	0.000	0.289	2.067	0.044
Dependent variable: VAR00001						

TABLE III. IMPEDANCE MATRIX

	CAP	BJR	CAS	TSC	TSR	GRT	BDG
CAP	1.000	0.729	0.677	0.606	0.569	0.534	0.440
BJR	0.729	1.000	0.929	0.831	0.779	0.732	0.603
CAS	0.677	0.929	1.000	0.895	0.839	0.789	0.650
TSC	0.606	0.831	0.895	1.000	0.875	0.774	0.677
TSR	0.569	0.779	0.839	0.875	1.000	0.876	0.788
GRT	0.534	0.732	0.789	0.774	0.876	1.000	0.900
BDG	0.440	0.603	0.650	0.677	0.788	0.900	1.000

TABLE IV. B_d VALUE

Zone	B_d
Cilacap	1.18.E-03
Banjar	9.35.E-04
Ciamis	8.95.E-04
Tasikmalaya City	8.98.E-04
Tasikmalaya Regency	8.44.E-04
Garut	8.30.E-04
Bandung	8.68.E-04

These balancing factors are used to adjust the model so that the predicted trips align with the fixed attractions in each zone. The narrow range of values indicates a relatively uniform attraction strength across the corridor. The final ODM

representing the daily flow of the fuel freight trucks from Cilacap to Bandung can be computed using the values of A_i , B_d , trip productions (O_i), trip attractions (D_j), and the impedance values (f_{id}), as shown in Table V. The flows of freight by fuel are highlighted, including the internal movement within Bandung (179 trucks) and the high flows from the Garut and Tasikmalaya regions. These patterns underscore the role of Bandung as both a generator and attractor of the fuel truck traffic. The resulting distribution of the fuel freight vehicle movements is visualized through computational modeling, as depicted in Figure 5.

C. Traffic Assignment Modeling

The traffic assignment model used in this study was developed through mathematical formulation and simulation. The analysis is predicated on the assumption of a uniform road capacity along the entire fuel freight transportation corridor. The simulation included various inputs, such as zonal boundaries, network nodes, link connections, link types, and connectors. The assignment process used the Lohse equilibrium model, which corresponds to the all-or-nothing approach in its method of traffic loading. The output of the simulation revealed the spatial distribution of the fuel freight movements across the corridor, as presented in Figure 6.

TABLE V. FINAL ODM OUTPUT (VEHICLES/DAY)

	CAP	BJR	CAS	TSC	TSR	GRT	BDG
CAP	34	9	13	10	16	16	25
BJR	19	10	14	11	17	17	27
CAS	18	10	15	12	19	19	30
TSC	16	8	14	13	20	18	31
TSR	30	16	25	22	45	40	71
GRT	26	13	22	18	36	42	75
BDG	46	24	39	34	69	82	179
D_j	190	90	142	120	222	234	439
D'_d	190	90	142	120	222	234	439
E_d	1.00	1.00	1.00	1.00	1.00	1.00	1.00
B_d	1.2E-03	9.4E-04	8.92E-04	9.0E-04	8.4E-04	8.3E-04	8.7E-04
O_i	122	114	123	120	250	233	474
O'_i	150	117	122	120	238	218	470
E_i	1.22	1.03	0.99	1.00	0.95	0.94	0.99
A_i	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$D_j \leftrightarrow O_i$					1436		
$D'_d \leftrightarrow O'_i$					1436		
$E_d \leftrightarrow E_i$					1.000		

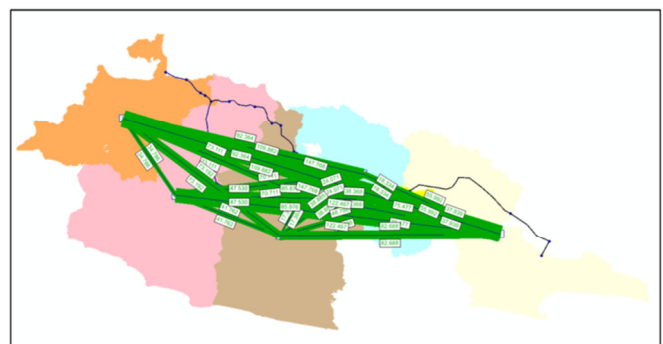


Fig. 5. Desire line diagram visualizing the daily fuel freight flows across the Cilacap-Bandung corridor based on the Origin-Destination Matrix. Thicker lines indicate higher traffic volumes between zones.

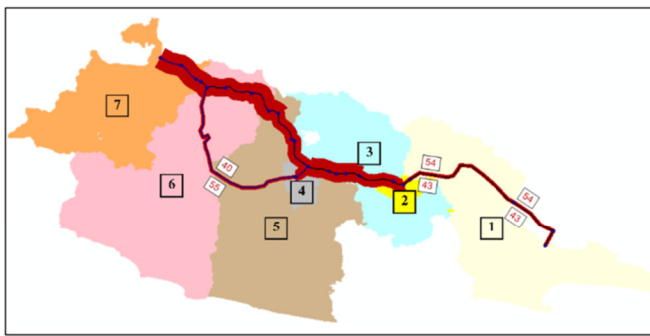


Fig. 6. Spatial distribution of fuel freight movements along the corridor under the current network conditions. Network segments are color-coded based on fuel freight volume intensity.

An evaluation of the current conditions reveals a significant imbalance in the fuel freight traffic flow along the corridor, as indicated by the uneven distribution of loads across various network segments. This can be analyzed by examining the relationship between the traffic volume and LoS, as shown in Figure 7. The demand curve (blue line), exhibits a negative exponential tendency, suggesting that as the LoS improves, the demand for fuel freight experiences a gradual decline, due to the enhanced delivery efficiency and optimized routes that are observed when the road conditions are favorable. Conversely, the supply curve (green), exhibits an increase, indicating that an enhanced LoS is conducive to supporting greater traffic volumes within the network as the service quality is elevated.

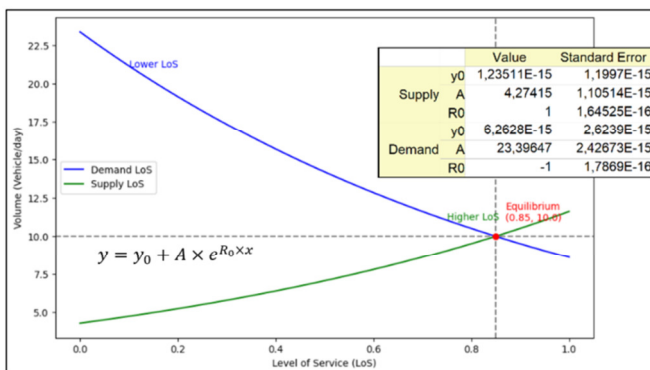


Fig. 7. Traffic demand and supply curves for fuel freight under the current conditions. The equilibrium point indicates the current (LoS ≈ 0.85) and corresponding freight volume (≈10 trucks/day).

The intersection points of these two curves, at an LoS of approximately 0.85 and a fuel freight volume of ten vehicles per day, demonstrated the current equilibrium in the system. This outcome is indicative of the prevailing conditions in Indonesia's fuel freight transport environment, where the persistent demand is constrained by infrastructural limitations [9, 12-14, 28]. Authors in [29], showed that there is a correlation between the infrastructure capacity and demand. This correlation is especially evident in urban areas, such as Jakarta, the previous capital city of Indonesia [30]. In such circumstances, congestion becomes a structural problem, leading to unreliable delivery times, higher operational costs, and increased risk to fuel supply continuity, particularly for

time-sensitive or hazardous fuel logistics [16, 26]. This study applied a network optimization and distribution planning model to enable a more balanced and efficient fuel freight flow. As illustrated in Figures 8 and 9, the optimized model attains a novel equilibrium at an LoS of approximately 0.49, accompanied by a reduced freight volume of 5.1 vehicles per day. This optimized scenario exhibited a substantial enhancement in the network performance, reaching a more stable operating condition, wherein the freight demand is better aligned with the supply, and the available road capacity is used more effectively. This transition toward a central equilibrium indicates a more robust and effective fuel-freight transportation network. By redistributing the traffic loads, the model enhances the network usage, alleviates the congestion, and reduces the travel time variability [7, 17, 24-26]. Most importantly, it strengthens the reliability of the fuel distribution, ensuring a timely and predictable delivery, even under variable traffic conditions. These findings underscore the strategic value of data-driven traffic modeling and simulations. These analytical tools are important for diagnosing operational inefficiencies and assessing the impact of the proposed interventions. By leveraging these quantitative insights, transportation planners and policymakers can design targeted, efficient, and sustainable freight mobility strategies, ultimately reinforcing the national logistics infrastructure and urban energy resilience [7, 8, 17, 19, 26, 31].

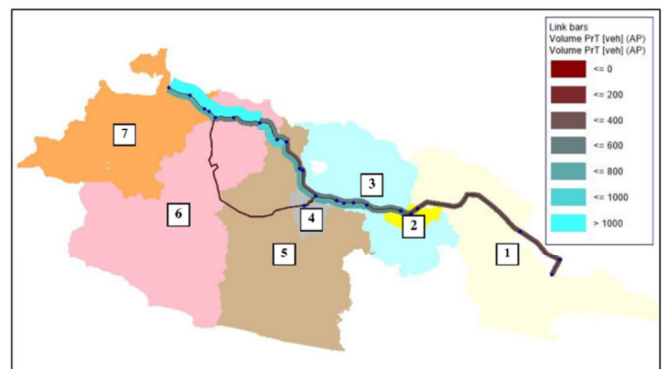


Fig. 8. Optimized fuel freight distribution model using traffic simulation and flow reallocation. The improved load balance reduces the volume and enhances the network efficiency.

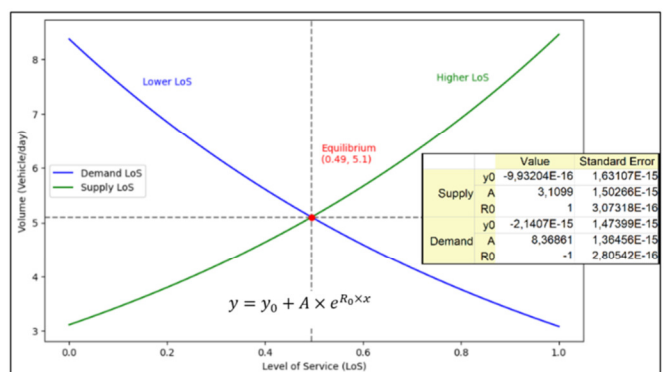


Fig. 9. Optimized traffic condition showing improved equilibrium at a lower LoS value (≈0.49) and reduced fuel freight volume (≈5.1 trucks/day), indicating increased delivery efficiency.

D. Policy Implications and a Framework for Resilient Fuel Distribution

The findings of this study underline the critical role of transportation modeling in informing the energy logistics policies. A strategic framework is proposed to enhance the stability of the fuel distribution systems, along the Cilacap–Bandung corridor. The framework is based on: diagnostic modeling, infrastructure prioritization, and dynamic management and optimization.

1) Diagnostic Modeling

The usage of gravity-based models and data-driven analyses to ascertain the most influential variables affecting the freight flows is analyzed. These variables include population, road conditions, and regional economic indicators. The findings of this study indicated that a model integrating these variables can accurately diagnose the network inefficiencies and identify the critical freight-generating zones. Using such diagnostic modeling provides an empirical foundation for informed decision-making and infrastructure planning [24-26]. The proposed framework enables a transition from reactive infrastructure management to predictive planning, wherein policymakers can anticipate logistical stress points before they become bottlenecks.

2) Infrastructure Prioritization

The simulation results from this study showed that enhancing the road conditions in key corridor segments improves the freight efficiency and reduces congestion. This finding is consistent with those of previous research, indicating that the infrastructure quality plays a crucial role in enhancing the freight throughput and operational reliability, particularly in regions with a significant reliance on road-based logistics [13, 16, 28]. This approach is based on prioritizing specific corridors, where high-impact routes are chosen for focused upgrades to optimize the efficiency, returns, and logistics performance.

3) Dynamic Management and Optimization

It is evident that static planning approaches often prove to be inadequate in addressing the intricate and constantly evolving nature of urban logistics. The adoption of traffic simulation and optimization, as evidenced by the LoS improvement from 0.85 to 0.49, signifies the framework's capacity to facilitate the testing of numerous scenarios, the dynamic redistribution of traffic loads, and the responsive management of real-time constraints. This approach aligns with the principles of equilibrium modeling [18], and is further validated by multi-objective planning tools in contemporary logistics research [22, 32].

The three pillars of this framework are designed to provide a structured, data-informed policy basis for enhancing the urban energy resilience, providing strategic guidance for long-term sustainability planning in addition to improving logistics efficiency. By identifying systemic weaknesses, allocating infrastructure investment to areas of highest need, and implementing dynamic management strategies, policymakers can minimize the fuel supply disruptions and enhance the delivery reliability, even in conditions of high demand or

unfavorable traffic circumstances. Moreover, the usage of this framework into national energy planning is congruent with broader sustainability and resilience objectives, particularly as developing countries, like Indonesia, confront mounting urbanization and energy consumption. It has been demonstrated that resilient infrastructure and robust distribution systems are important to achieving secure, low-carbon, and equitable energy access [7, 19, 29].

IV. CONCLUSIONS

The present study developed a gravity-based transportation model for fuel freight distribution along the strategic Cilacap–Bandung corridor in Indonesia. The model's ability to successfully predict the freight movements is attributable to its integration of regression analysis with traffic assignment and simulation techniques, which enabled the capture of the relationships among demographic, economic, and infrastructural variables. The research identified key inefficiencies in the current system, such as uneven load distribution and limited delivery reliability, which threaten the urban energy resilience. The study's findings have yielded a substantial improvement in equilibrium, achieved through the usage of optimization modeling. This enhancement involved a reduction in the daily freight volumes and an improvement in the Level of Service (LOS). These improvements underscore the practical value of the quantitative modeling in addressing complex transportation challenges. The findings contribute to the emerging discourse on sustainable logistics and urban energy resilience, offering a replicable framework for policymakers and planners in other developing regions facing similar infrastructure and energy security issues. The model has some limitations due to the fact that it is based on data from a single, albeit strategic, corridor. Therefore, applying and validating this framework on other energy distribution routes with different characteristics would enhance its generalizability. Secondly, the analysis is predicated on the assumption of a uniform road capacity, with no consideration given to dynamic, real-time traffic variations or incidents, while the study's primary focus is centered on the intricate dynamics of the fuel freight. However, a more advanced model could explore the intricate interactions between the fuel trucks and other freight vehicles that are engaged in a competitive race for limited road space. Consequently, future research should aim to expand this model into a multi-corridor, multi-commodity network. Integrating a comprehensive cost-benefit analysis of infrastructure improvements and policy interventions would also provide more robust support for the investment decisions. Finally, exploring the potential of alternative transportation modes, even in areas where the road transport is significant, could reveal new strategies for a more resilient and sustainable national energy logistics system.

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