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Analysis of Road Network Vulnerability for Dempo Volcano Eruption Evacuation

Gita Aprilia, Hardiansyah, Lindung Zalbuin Mase, Rena Misliniyati, Khairul Amri
Civil Engineering Department, Universitas Bengkulu, Bengkulu, 38122, Indonesia

E-mail: gitaap23@gmail.com

ABSTRACT
South Sumatra is a province on the island of Sumatra, positioned along the boundary between the Indo-Australian Plate and the Eurasian Plate. The tectonic interaction between these plates has resulted in a mountain range that extends longitudinally from the island's northern to southern regions, a geological condition that contributes to the area's susceptibility to natural hazards, one example is the Dempo Volcano. This study uses the four-step model method to analyse the vulnerability of the road network on evacuation routes during the eruption of Dempo Volcano in Pagar Alam City. Eight road sections were observed. A comparison of traffic survey results and numerical modelling was conducted to assess the consistency of the model and also to predict critical conditions. Scenario 1 represents evacuation conditions without any changes to road geometry, while Scenario 2 represents evacuation conditions with modifications in the form of road widening. The analysis showed that most of the population prefers motorcycles as a mode of transport and the fastest route during evacuation, considering the faster evacuation time. Scenario 1 showed a surge in traffic volume, which became an obstacle to evacuation. Scenario 2 can increase capacity and improve traffic flow. The Vulnerability Index indicates that some road sections are vulnerable to evacuation impacts.

Keywords: *Disaster Evacuation; Four Steps Models; Dempo Volcano Eruption; Road Network Modelling; Vulnerability Index.*

1. Introduction

South Sumatra is one of the provinces on the island of Sumatra, located at the border of the Indo-Australian Plate and the Eurasian Plate. The activity of these two plates has formed a mountain range stretching from north to south across the island of Sumatra, with this condition potentially causing natural disasters [1]. Pagar Alam is one of the areas at high risk of volcanic eruptions due to an active volcano, Dempo Volcano, with a height of 3,173 metres above sea level, which has historically experienced small-scale eruptions since 1817 [2].

Given this region's high risk of disaster, various mitigation concepts and strategies are needed [3]. One important strategy in mitigation is evacuation, which is moving individuals from dangerous areas to safer locations to reduce risks to the safety of affected communities [4]. The disaster evacuation process can cause vulnerability in road networks due to traffic volume spikes, infrastructure limitations, and environmental conditions. Therefore, it is necessary to identify the performance of road networks used during evacuation to evaluate the readiness of road capacity in serving traffic volume [5].

Road network vulnerability in transportation refers to the potential risk of incidents that can cause a significant decline in the ability of the road network to provide services, thereby impacting the smooth flow of transportation [6]. Therefore, road network performance analysis is an important initial step before determining the level of vulnerability. Road network performance is generally measured through indicators such as traffic volume, road capacity, and degree of congestion, which reflect how optimally the transportation system functions under certain conditions. Road network vulnerability analysis typically involves modelling to compare road network performance under

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normal conditions and during disasters [7]. One method used is the *four-step model*, which consists of four main stages trip generation, trip distribution, mode choice, and trip assignment [8].

This is the first study to explicitly integrate the four-step transportation model into volcanic disaster evacuation planning in Indonesia, particularly in high-risk areas such as Pagar Alam City. In contrast to previous approaches, which are generally based on static spatial analysis or shortest-path algorithms that fail to account for traffic dynamics during evacuation, this study directly incorporates evacuation movement patterns into analysing road network performance. The methodological breakthrough of this study offers an innovative approach by integrating the four-step transportation model into dynamic simulation within the context of volcanic disaster evacuation. Furthermore, this study develops an operational road network vulnerability index that local governments and disaster management agencies can utilise to identify critical road segments during evacuation. This approach offers a significant practical contribution to emergency disaster response planning by providing a robust analytical foundation for designing evacuation systems that are responsive, adaptive, and grounded in local data.

Previous studies [9], [10], and [11] used Geographic Information Systems (GIS) to map evacuation routes spatially. This approach effectively visualises affected areas and provides an overview of potential geographical risks. However, GIS-based mapping is still limited to static mapping and does not represent traffic flow dynamics during evacuation. Meanwhile, [12] applied Dijkstra's Algorithm to mathematically determine the shortest evacuation route. Although efficient in finding routes based on distance or time, this algorithm does not consider traffic conditions and network capacity changes, which are crucial in disaster situations. This limitation is important because evacuation depends on distance and the network's ability to accommodate traffic dynamically.

In response to these limitations, [13] developed an integrated approach that combines a four-step model with road network vulnerability analysis. This approach can dynamically simulate traffic flow at a macroscopic scale and identify critical points in the network based on capacity and reliability. However, no studies have applied this approach in the Dempo Volcano area, which has distinct geographical, infrastructure, and population density characteristics compared to other regions. Therefore, this study addresses the methodological gap by integrating traffic dynamics, network capacity, and local characteristics into evacuation simulations. The findings from this study are expected to contribute to the development of more adaptive transportation-based disaster mitigation strategies and support resilient urban planning against disaster risks, particularly for the Dempo Volcano.

2. Material and Method

2.1. Study Area

This study was conducted on 5-6 April 2025 in the road network of Dempo Volcano Village, Pagar Alam City, which is within a 5 km radius of the summit of Dempo Volcano, as shown in Figure 1. This location was chosen because it is a major tourist centre with high vulnerability to eruption. The high intensity of tourist visits, population settlements, and limited access are crucial factors that reinforce the urgency of effective evacuation planning. This study aims to analyse the vulnerability of the road network in supporting the evacuation process through transport modelling using the four-step model.

This approach is used to identify road sections that have a strategic role in maintaining regional connectivity and ensuring the movement of the population to safe evacuation points. The scope of the study includes several main road sections that have a vital role in supporting community mobility during emergencies, including Rimau Pariwisata Road, Rimau Kampung 4 Road, Rimau Road, Soekarno Hatta Road, Amat Ramui 1 Road, Amat Ramui 2 Road, Laskar Wanita Mentarjo 1 Road, and Laskar Wanita Mentarjo 2 Road. The analysis focused on the vulnerability of the road network in terms of accessibility and connectivity between sections to maintain the overall network function when facing potential disruption or damage due to volcanic activity.

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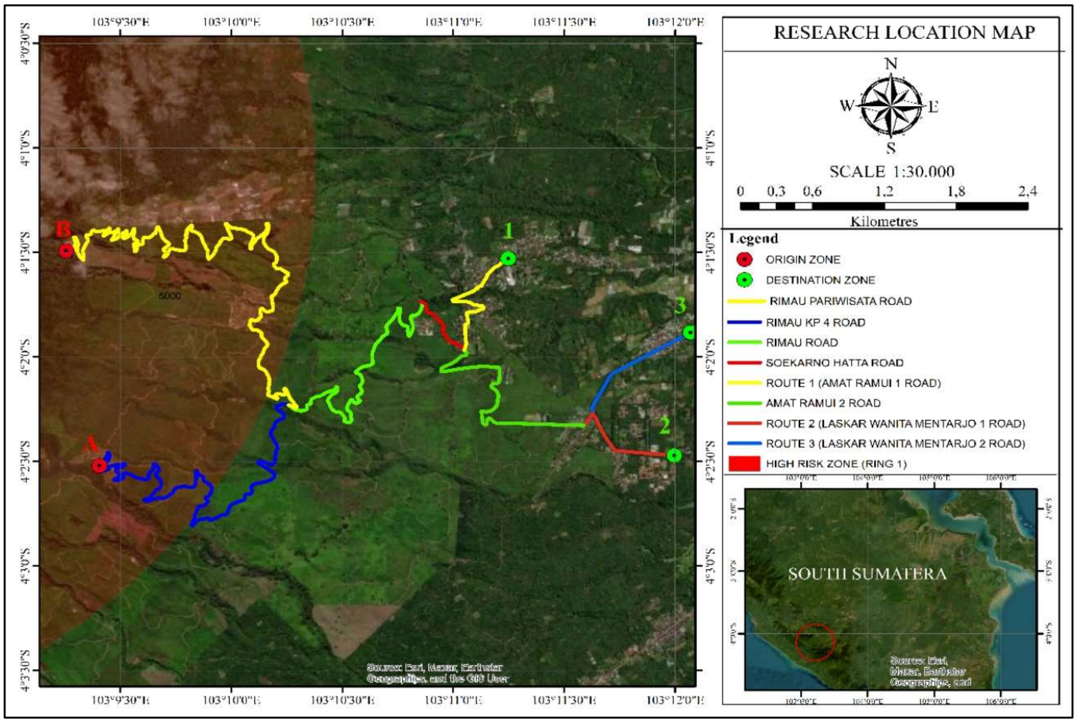

Figure 1. The layout of the study area

2.2. Data Collection

The data used in this study consist of primary and secondary sources that complement each other in the analysis. Primary data was obtained through field surveys that included observations of traffic flow during peak hours, measurements of road geometric conditions, and the distribution of questionnaires to residents of Dempo Volcano Village to obtain information on the origin and destination of trips, modes of transportation used, and estimated evacuation times. The daily traffic flow survey was conducted over six hours, covering peak hours, morning (06:30-08:30 WIB), midday (12:00-14:00 WIB), and evening (16:00-18.00). Meanwhile, secondary data was obtained from various relevant agencies, including road network maps of Pagar Alam City, population data within a 5 km radius of the disaster-prone zone, tourist visitation data to the mountainous area, and disaster-related data from the Pagar Alam City Disaster Management Agency (BPBD), which includes information on potential threats and disaster mitigation policies.

2.3. Sample and research population

The Dempo Volcano subdistrict comprises two villages that served as the study locations, namely Kampung 2 and Kampung 4, with a total population of 289 people. To obtain primary data on the characteristics of community evacuation, a sample of 10% was selected, resulting in 29 respondents. In addition, questionnaires were distributed to tourist groups considered a vulnerable population in the context of a Dempo Volcano eruption. Based on visitation records, the number of tourists reached 14.400 individuals, from whom 1%, or 144 respondents, were sampled.

Sample size determination followed the guidelines outlined in the references [15], which specify varying percentages according to population size. For populations ranging from 0 to 100, the entire population (100%) is taken as the sample, for populations between 101 and 1.000, 10% is taken, for those between 1.001 and 5.000, 5% is used, for populations between 5.001 and 10.000, 3% is selected, and for populations exceeding 10.000, 1% is taken. These proportions provided the basis for calculating appropriate sample sizes in this study. The sampling method applied was non-probability sampling, specifically accidental sampling. This approach involves selecting individuals based on chance encounters, meaning that anyone who happens to meet the researcher and is

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considered appropriate could be included as a respondent. [16]. The primary criterion for inclusion was that participants had to be residents of the Dempo Volcano area, which is classified as a region at risk of volcanic eruption.

2.4. Evacuation Modelling Using the Four-Step Model

Evacuation is important to disaster response [14]. Therefore, a transportation modelling approach is needed to support evacuation [15]. Evacuation modelling generally covers a large study area and involves several links and zones, so model development falls under the macroscopic category. Macroscopic models are used to evaluate the performance of transportation networks during emergency evacuations in large-scale areas [16].

This study conducted a performance-based road network evacuation modelling using the four-step trip generation, trip distribution, mode choice model, and trip assignment models [8]. The trip generation model is the initial stage in transportation modelling used to estimate the number of trips originating and terminating in a zone/area within a specific period, particularly from disaster-prone to safe zones. These estimates are based on population size, land use, and socio-economic characteristics in each zone [17]. The trip distribution model is a form of transportation modelling used to estimate the number of trips from a source zone (disaster-prone area) to various destination zones (such as evacuation sites) or vice versa, from several source zones to one or more destination zones. This source-destination matrix model describes travel patterns between zones within the study area [18]. The mode choice model is a stage of transportation modelling that determines the number of people who choose a particular mode of transportation to meet their travel needs from their origin to their destination according to their travel purpose. The trip assignment model is a model that predicts travel route choices and traffic distribution in the transportation network connecting the origin to the destination [8].

The four transportation models are integrated systematically in their implementation within the software. In the trip generation stage, the number of trips in each zone is estimated based on population data and vehicle ownership. The output from this stage serves as input for the mode choice model, which utilizes questionnaire data related to selecting transportation modes for evacuation. This information is then combined with the results of questionnaires on evacuation routes, which are used in the trip assignment stage to determine the direction of travel distribution. These three components are used to construct the origin-destination matrix in the trip distribution model, which is then calibrated using the Furness method, an iterative process based on survey data until equilibrium between the origin and destination zones is achieved. The entire modelling process uses the ZIN Macrosimulation software, which integrates all four modelling stages to simulate macroscopic traffic flow and provide a realistic representation of field conditions [19]. Although this model can describe traffic flow on a macroscopic level, it should be noted that this approach does not fully capture the complexity of individual behavior in emergencies. Evacuation decisions in the field are often influenced by emotional factors, panic, or limited access to information during a disaster, which are challenging to represent fully through a static data-based model.

2.5. Model Validation

As part of the quality control measures in this study, the model was then validated by comparing the volume of the field survey results with the modelling results. The validation process was carried out using the R^2 determination coefficient as a statistical indicator to assess the level of conformity between the modelling results and the actual conditions in the field. In this study, the model was considered valid if the R^2 value was ≥ 0.75, indicating that the model had a high level of accuracy in representing actual conditions. The equation for calculating the determination coefficient is as follows [20]:

$$R^2 = 1 - \frac{\sum \left(y_i - \hat{y}_i \right)^2}{\sum \left(y_i - \bar{y} \right)^2} \tag{4}$$

where:

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R^2 = Coefficient of determination
y_i = Actual value of the field survey results
$\hat{y}_i$ = Predicted value of the modelling results
$\overline{y}$ = Average of all actual values, $\sum$ is the total number.

Uncertainty in evacuation modelling arises from the limitations of models in comprehensively representing real conditions, especially in translating survey traffic volumes into origin-destination matrices between zones. This process involves an iterative approach that can produce bias because it does not fully describe actual movement patterns. To reduce this uncertainty, this study validated by comparing the software's traffic volume simulation results with daily traffic volume data obtained through surveys. In macroscopic modelling, a validity value of 0.75 or higher is generally considered sufficient to represent actual conditions in the field. Therefore, the level of agreement obtained from the validation results indicates that this model is reliable enough for evacuation planning.

2.6. Modelling Framework

The methodological stages in this study were compiled and presented in a flow chart, as shown in Figure 2. The study began with collecting data from the Dempo Volcano area, which faced evacuation problems during the eruption that affected the community of Pagar Alam City. Data was collected from two sources: primary and secondary data. Primary data included observations of traffic flow during peak hours, road geometry, and questionnaire results from residents and tourists within a 5 km radius of the mountain peak. Meanwhile, secondary data was obtained from road network maps, population data, and the Regional Disaster Management Agency (BPBD) information.

After collecting the data, traffic flow, road capacity, and questionnaire results were processed. Analyses were conducted to identify patterns in the community's evacuation route selection. Based on these results, an origin-destination matrix was constructed by integrating the trip generation and distribution models. The matrix was calibrated iteratively using the Furness method to ensure a balance between trip generation and distribution. The developed model was then validated using actual traffic flow data from field surveys. After successful validation, simulations were continued with two modelling scenarios. Scenario 1 Evacuation traffic flow simulation while maintaining existing road geometric conditions. Scenario 2 Evacuation simulation with a road capacity increase scenario as a modification to the existing geometric conditions. The results of both scenarios were analysed and compared to obtain a comprehensive picture of the effectiveness of the proposed evacuation scenarios. The findings from this analysis formed the basis for discussion and conclusions.

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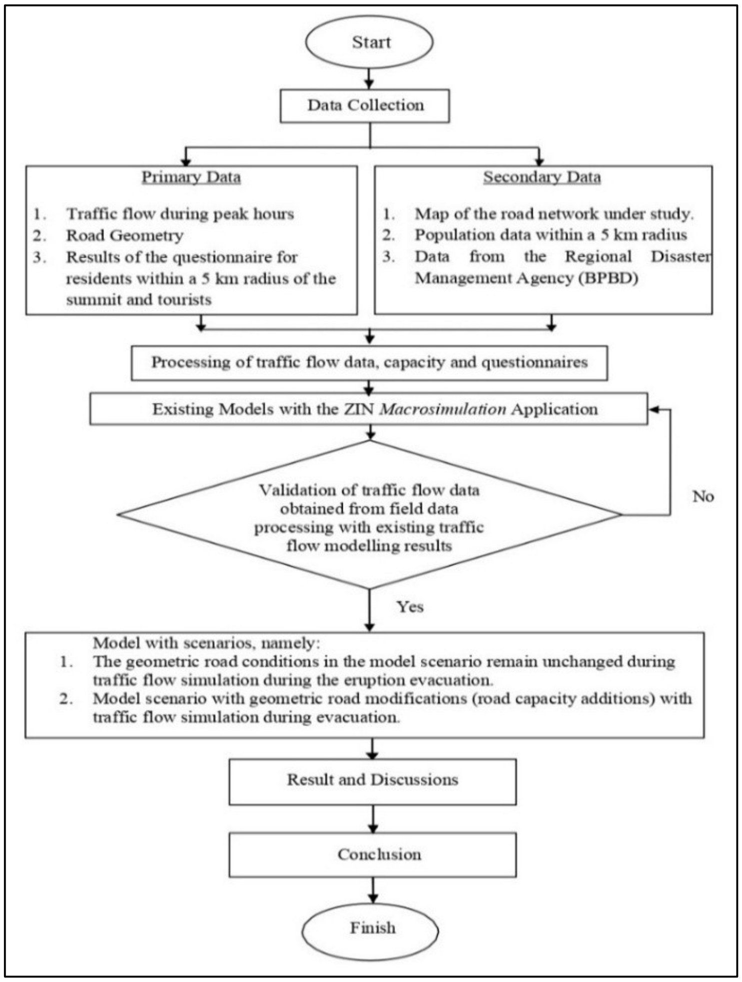

Figure 2. Research Flowchart

2.7. Road Network Performance

Road network performance describes the conditions on a road network based on quantitative measurements, such as road capacity, average speed, travel time, and degree of saturation. The degree of saturation is influenced by traffic volume and road capacity, with the ideal degree of congestion being 0.85. Capacity is the maximum flow maintained along a specific road segment. The equation for determining capacity is as follows:

$$C = C_O \times FC_{LJ} \times FC_{PA} \times FC_{HS} \times FC_{UK} \quad (1)$$

where :
C = Road capacity (light vehicles unit (lvu)/hour)
C_O = Basic capacity (light vehicles unit/hour)
FC_{IJ} = Capacity adjustment factors related to lane width or traffic lanes
FC_{PA} = Capacity adjustment factors related to directional dividers (only on undivided roads)
FC_{HS} = Capacity adjustment factors related to side obstacles and road shoulders
FC_{UK} = Capacity adjustment factors related to city size.

The degree of saturation is the ratio of traffic flow to road capacity [21]. The degree of saturation is a key indicator for assessing road network performance, showing the extent to which road capacity is used and the potential for capacity problems on road segments. The general equation is as follows:

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$$Ds = \frac{Q}{C} \tag{2}$$

where:

D_S = Degree of saturation
Q = Total traffic flow (lvu/hour)
C = Capacity (lvu/hour).

According to [22], six classes determine the level of service based on the degree of saturation value. Level A for $0 \leq D_S < 0.20$ indicates free flow with high velocity and low volume. Level B $0.21 \leq D_S < 0.44$ indicates stable flow even though the velocity is starting to be limited. Level C ($0.45 \leq D_S < 0.74$) indicates stable flow with controlled velocity. Level D ($0.75 \leq D_S < 0.84$) indicates a nearly unstable flow with controllable velocity. Level E: $0.85 \leq D_S < 1.00$ indicates unstable flow with frequently interrupted velocity. Level >1.00 indicates very dense flow with congestion.

2.8. Network Vulnerability Index

Vulnerability can be defined as the response of a transportation system and the ability of a road network to adapt to a form of exposure or disturbance, such as natural disasters [23]. This study analyzed the Dempo Volcano area using daily road network modelling with road conditions during evacuation. This study refers to research results [5], which developed a vulnerability index by comparing road network performance based on differences in volume on each road section. Therefore, if the resulting index value is positive, the road network is considered vulnerable; conversely, if the index value is negative, the road network is deemed non-vulnerable. The road network vulnerability index based on traffic volume is shown in the following equation:

$$INVE_T = \left[\frac{\left(\sum_{i=1}^{|X|} F_E\right) - \left(\sum_{i=1}^{|X|} F_D\right)}{\left(\sum_{i=1}^{|X|} F_D\right)} \right] \tag{3}$$

where:

$INVE_T$ = Road network vulnerability index
F_D = Total daily volume
F_E = Total evacuation volume.

3. Result and Discussion

3.1. Research Questionnaire

Before the analysis, a questionnaire was conducted to collect primary data on community movement characteristics in emergency conditions. The survey aimed to obtain information on evacuation route choice patterns. The questionnaire results are an important foundation for the four-step model's trip generation and distribution stages. Figure 1 shows the layout of the study area. The map divides the area into two origin zones, zone A and zone B, which are residential areas and tourist concentrations within the disaster-prone radius.

Meanwhile, the destination zone is divided into three areas, namely zone 1, zone 2, and zone 3, which are designated as safe evacuation points based on recommendations from the BPBD of Pagar Alam City. Table 1 summarises the results of a questionnaire survey of 173 respondents. The data shows that most respondents used motorcycles as their mode of transport during evacuation, with the majority evacuating to point 1.

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Table 1. Summary of Questionnaire Results

No	Zone	Total Respondents	Evacuation Transportation		Evacuation Route		
			Motorcycle	Car	Route 1	Route 2	Route 3
1	A	5	4	1	5	0	0
2	B	168	145	23	84	48	36

The questionnaire survey results of 173 respondents indicate that 52% selected Zone 1, 27% selected Zone 2, and 21% selected Zone 3. In zone A, 100% selected zone 1. Meanwhile, in zone B, 42% chose zone 1, 33% chose zone 2, and 25% chose zone 3. The results of this questionnaire not only support the trip generation and trip distribution stages but also provide a basis for mode choice and trip assignment by identifying transportation modes and evacuation directions chosen by respondents. This shows that the empirical approach of the survey has been successfully integrated into the conceptual structure of the transportation model, thereby increasing the reliability of the modelling results while strengthening the relationship between the theoretical framework and its practical application in the field.

3.2. Road Capacity Analysis Results

Road capacity analysis is calculated based on the results of a geometric road survey to determine the maximum volume that can be served by each road segment based on existing conditions. The calculation begins with the base capacity, followed by adjustments for several factors, such as capacity correction factors due to lane differences, capacity correction factors due to directional dividers on undivided roads, capacity correction factors due to side obstacles on roads with shoulders, and capacity correction factors based on city size. Table 2 shows the capacity calculation results for each road segment.

Table 2. Road Capacity

Road Name	Basic Capacity	Adjustment Factor for Capacity				Capacity (pcu/hour)
		FC_{LJ}	FC_{PA}	FC_{HS}	FC_{UK}	
Rimau Pariwisata Road	2800	0.56	1	0.96	0.86	1294.5
Rimau Kampung 4 Road	2800	0.56	1	0.96	0.86	1294.5
Rimau Road	2800	0.56	1	0.96	0.86	1294.5
Soekarno Hatta Road	2800	0.56	1	0.96	0.86	1294.5
Amat Ramui 1 Road	2800	0.56	1	0.96	0.86	1294.5
Amat Ramui 2 Road	2800	0.56	1	0.99	0.86	1335.0
Laskar Wanita Mentarjo 1 Road	3400	1.00	1	1.02	0.86	2982.5
Laskar Wanita Mentarjo 2 Road	3400	1.00	1	1.02	0.86	2982.5

3.3. Comparison of Traffic Flow Volume between Modelling Results and Field Surveys under Existing Conditions

A comparison between the traffic volume resulting from the modelling and the field survey data was conducted to assess the extent to which the model could represent actual conditions in the field. This process was part of the model validation process using a simple linear regression approach. Table 3 presents the model statistics, while Figure 3 presents a comparison graph of surveyed traffic volume and model results.

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Table 3. Statistical Validation Model

Road Name	Mean	Median	Modus	Standard Deviation	Absolute Error
Rimau Pariwisata Road	1115.83	1115.83	1120	4.17	8.35
Rimau Kampung 4 Road	69.84	69.84	70.10	0.27	0.53
Rimau Road	1127.15	1127.15	1125.60	1.55	-3.10
Soekarno Hatta Road	1155.35	1155.35	1182	26.65	53.30
Amat Ramui 1 Road	916.36	916.36	919.70	3.34	6.67
Amat Ramui 2 Road	1024.52	1024.52	1143.20	118.68	237.35
Laskar Wanita Mentarjo 1 Road	655.96	655.96	658.70	2.75	5.49
Laskar Wanita Mentarjo 2 Road	1012.42	1012.42	1016.30	3.88	7.76

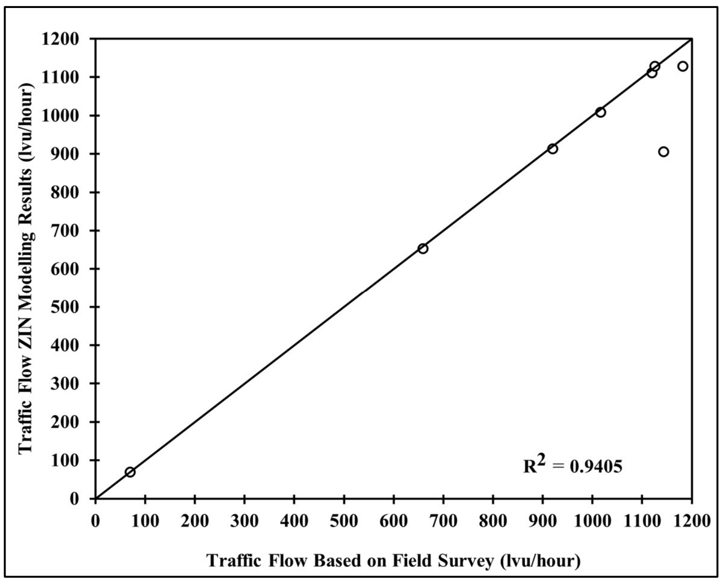

Figure 3. Comparison Graph of Surveyed Traffic Volume and Model Results

The results of linear regression analysis yielded a coefficient of determination value of 0.9405, indicating that 94.05% of vehicle volume on road segments based on daily conditions and modelling results are valid. This level of accuracy reflects that the model structure has successfully represented the actual traffic characteristics in the field. An R^2 value above 0.75 in transportation modelling indicates a suitable model for scenario analysis, particularly in evacuation planning. This finding reinforces the validity of the four-stage approach used in this study, particularly in the distribution and assignment stages. With this validation, it can be concluded that the model built is suitable for evacuation scenario simulations and has a high level of reliability in data-driven transportation decision-making.

3.4. Road Network Performance Results Analysis

According to traffic performance criteria, a road section is considered saturated if its saturation level exceeds 0.84. Figure 4 compares the degrees of saturation for each scenario. Based on field survey results, the saturation level on road segments during daily conditions varies between 0.05 and 0.91. This indicates that road performance ranges from very good to saturated conditions.

Scenario 1 modelling was conducted during the eruption without changes to the geometry of the road. In Figure 1, the modelling was simulated by assuming vehicle movements originating from

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the source zone, residential areas, and tourist centres, located within a 5 km radius of the eruption centre, towards three evacuation routes, which are the destinations. The modelling results show a significant increase in the congestion on Rimau Road from 0.87 to 1 due to evacuation movements. This value indicates that the road section is congested, which can hinder the smooth evacuation process, reduce travel time efficiency, and increase safety risks for evacuees. Subsequently, traffic flow is distributed towards three evacuation directions, significantly decreasing congestion levels on the Amat Ramui 1 road section from 0.71 to 0.40.

Scenario 2 was implemented to reduce congestion with geometric modifications in road widening on segments with low service levels. Simulation results show that this strategy effectively increases road capacity and improves overall network performance. This is reflected in the decrease in the saturation level of Rimau Road from 1 to 0.56 after the intervention. The research findings indicate that geometric modifications can enhance road network efficiency, particularly in supporting smooth evacuation. This capacity enhancement strategy can be optimised as part of disaster risk mitigation efforts based on the transportation system. The implications of these results are significant in the context of transport system-based evacuation planning. Identifying congested road sections and the effectiveness of geometric modifications provide a basis for technical decision-making and strategic policy-making. Therefore, integrating congestion patterns and road network performance evaluation is crucial in developing practical, adaptive, and responsive emergency evacuation plans.

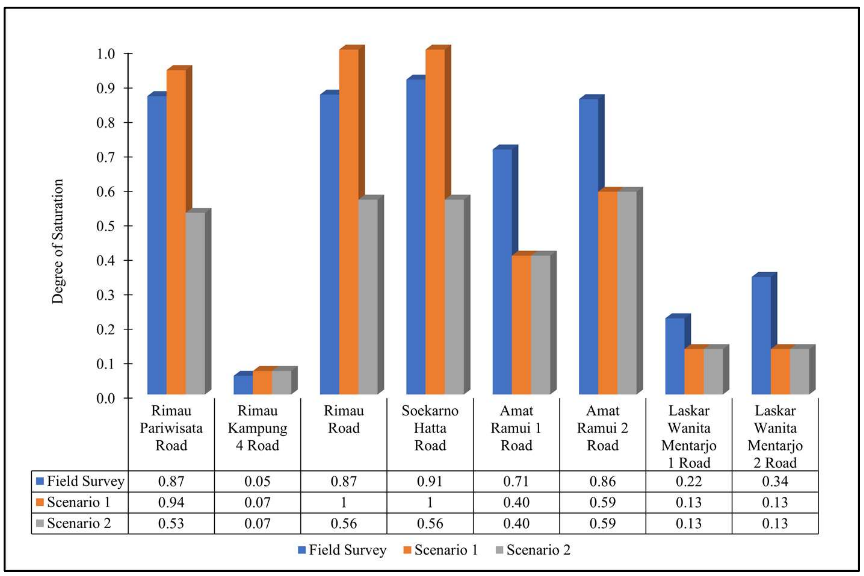

Figure 4. Comparison of Degree of Saturation for Each Scenario

Transportation capacity enhancement strategies can be optimised for disaster risk mitigation, particularly by ensuring the smooth flow of evacuation routes during a volcanic eruption. Simulation results show the distribution of traffic volume during the evacuation process, which is displayed spatially in Figure 5. The red sections of the road indicate hefty vehicle volume and are close to the maximum load capacity; green indicates moderate, relatively smooth traffic conditions, and light blue indicates smooth traffic flow. Conversely, dark blue indicates road conditions with very low traffic volume or nearly unused roads. The sections marked in white represent one-way lanes specifically directed toward safe locations as part of traffic engineering strategies to prevent movement toward hazardous zones and maximise evacuation efficiency. Red sections require intervention, such as road widening, to increase capacity and facilitate evacuation. Meanwhile, green-to-blue sections can be safer and more efficient alternative routes.

This approach complements previous studies that used GIS-based network analysis to determine evacuation routes by adding a dynamic dimension through macroscopic simulations based on vehicle

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movements. These simulations not only consider the spatial structure of the road network but also traffic volume dynamics and vehicle interactions during the evacuation process, resulting in more realistic and adaptive road access planning for various disaster scenarios.

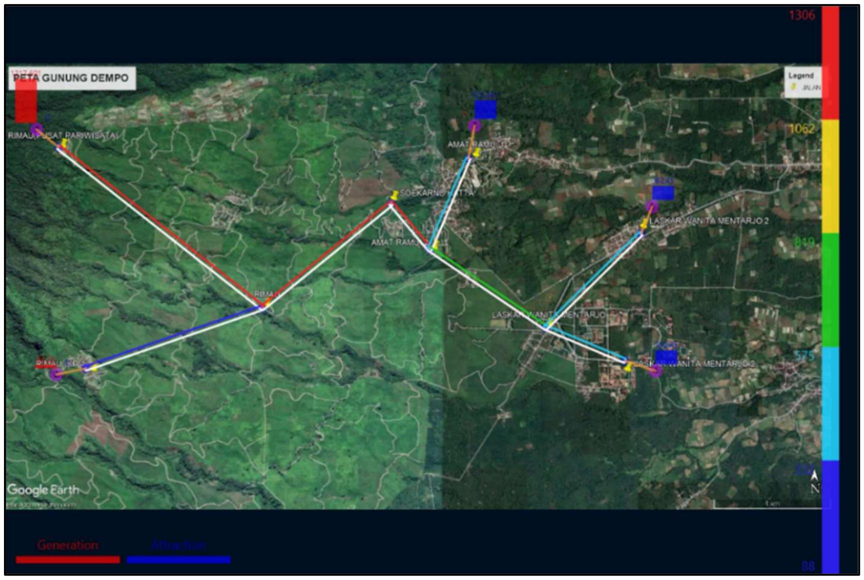

Figure 5. Mapping Traffic Flow Distribution on Evacuation Routes

3.5. Analysis of Road Vulnerability Index to Erupsi Disaster Evacuation

The vulnerability index value is calculated using the $INVE_T$ formula, which compares road network performance based on traffic flow differences on each road section between daily conditions and during evacuation. A positive value on the vulnerability index indicates that a road segment is vulnerable to volcanic eruptions. This is due to increased traffic density during the evacuation process, which makes road users more vulnerable to hazards. Table 4 shows the results of the road vulnerability index calculations.

Table 4. Road Vulnerability Indeks

Road Name	Daily Traffic Flow (unit/hour)	Traffic Flow Evacuation (unit/hour)	$INVE_T$
Rimau Pariwisata Road	1120.00	1217.60	0.0871
Rimau Kampung 4 Road	70.10	88.28	0.2593
Rimau Road	1125.60	1305.88	0.1602
Soekarno Hatta Road	1182.00	1305.88	0.1048
Amat Ramui 1 Road	919.70	520.98	-0.4335
Amat Ramui 2 Road	1143.20	784.90	-0.3134
Laskar Wanita Mentarjo 1 Road	658.70	392.45	-0.4042
Laskar Wanita Mentarjo 2 Road	1016.30	392.45	-0.6138

Based on the table, it can be concluded that Rimau Pariwisata Road, Rimau Kampung 4 Road, Rimau Road, and Soekarno Hatta Road have positive vulnerability index values, meaning that these roads are vulnerable to the impact of evacuation. Meanwhile, Amat Ramui 1 Road, Amat Ramui 2 Road, Laskar Wanita Mentarjo 1 Road, and Laskar Wanita Mentarjo 2 Road have a negative

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vulnerability index, meaning that these roads are not vulnerable to evacuation impacts. The visualisation of the vulnerability index values can be seen in Figure 6.

Figure 6. Distribution of Road Vulnerability

Figure 6 shows the spatial distribution of road vulnerability based on the calculated $INVE_T$ values. Road sections classified as vulnerable are depicted in different colours to facilitate visual identification of locations likely to experience obstacles during evacuation. This mapping serves as a tool in the planning process, particularly for determining priorities for infrastructure improvements, emergency traffic management, and the more effective deployment of evacuation resources. Thus, road network vulnerability analysis forms an important foundation for disaster mitigation strategies, especially in identifying critical locations that require greater attention in route planning and evacuation scenarios.

4. Conclusion

This study analyses the performance and vulnerability of the road network in the context of the Dempo Volcano disaster evacuation in Pagar Alam City. Road network performance is analysed based on the degree of saturation as an indicator of road section service levels. The modelling results show that under existing conditions, some road sections, such as Soekarno Hatta Road and Rimau Road, have a saturation degree value > 0.84, indicating a high potential for congestion during the evacuation process. In scenario 1, traffic congestion levels increase on main roads but are distributed across several evacuation routes, causing other road sections to experience a decrease in congestion levels. Interventions through Scenario 2, involving road widening, were proven to increase road capacity and reduce congestion levels significantly. This macroscopic simulation demonstrates that a model-based approach is more adaptive than conventional methods based on static assumptions. Therefore, road widening on Soekarno Hatta Road and Rimau Road is prioritised and integrated into the local government's strategic evacuation transportation plan.

Vulnerability analysis was conducted using the Vulnerability Index (VI) approach to identify road sections with the highest potential risk during the evacuation. The analysis results indicate that Rimau Kampung 4 Road (VI = 0.259) and Rimau Road (VI = 0.160) are the most critical segments and have the potential to become bottlenecks. Therefore, it is recommended that these critical segments be addressed through road repairs, traffic flow reorganisation, or the provision of alternative evacuation routes. This study focuses on the macroscopic modelling of road networks to support disaster evacuation planning with a data-driven approach responsive to disaster dynamics

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and potentially applicable in other vulnerable areas. However, the model does not fully cover the complexity of population behaviour during evacuation. To strengthen the results obtained, further studies are recommended to integrate a more dynamic approach to capture individual behaviour variability in emergencies.

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