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Article

Evaluation of The Road Vulnerability Network During the Evacuation Process (A Case Study in A Coastal Area of Bengkulu City, Indonesia)

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Abstract. This study aims to determine the road network's performance for the Pantai Panjang and Bencoolen Mall areas in Bengkulu City, Indonesia, if a tsunami disaster occurs. The traffic on roads and questionnaire survey on respondents who occasionally come to the study areas is performed. The numerical analysis is conducted using four-step modelling based on various road condition scenarios to evaluate the road network performance. Scenario 1 considers existing conditions during tsunami evacuation; Scenario 2 considers increasing road capacity and adding two new road sections using traffic flow simulation during tsunami evacuation; Scenario 3 considers the addition of one new road section using traffic flow simulation during tsunami evacuation. For Scenarios 4, 5 and 6, the previous scenarios are evaluated by considering the increase in vehicle numbers in the next five years. Scenarios 1 and 4 show that there is an increase in the degree of saturation up to 0.68. It shows that the level of road service decreases. The road modification scenarios (Scenarios 2 and 3) show improved service levels. The modelling results with scenarios using traffic flow data under the improvement of road service for the next five years (Scenarios 5 and 6) show that the level of road service is better than the existing model. The road modifications scenario also effectively reduces the vulnerability index. The local government could also consider the results to improve the tsunami disaster mitigation in the study area.

Keywords: Tsunami disaster, road network modelling, road network performance, vulnerability index.

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1. Introduction

Bengkulu City of Indonesia is an area located on the coast of the island of Sumatra, which was formed in a subduction area, namely the subduction of the Indo-Australian plate against the Eurasian plate [1, 2, 3]. Bengkulu is also an area with many settlements and tourist attractions near the coast, which means the risk of a tsunami will be even greater [4]. Mase [5,6] mentioned that there had been two strong earthquakes that hit Bengkulu City and its surrounding area within the last two years, i.e., the Bengkulu-Enggano Earthquake in 2000 (M_w 7.9) and the Bengkulu-Mentawai Earthquake in 2007 (M_w 8.6). Farid and Mase [7] and Mase *et al.* [8] also suggested that implementing spatial development refers to hazard mitigation. Mase *et al.* [9] and Qodri *et al.* [10, 11] suggested that pre-analysis of hazard analysis, such as seismic hazard should be performed before conducting mitigation plans. One of the issues with implementing hazard mitigation is the evacuation process when the hazard comes. As the coastal area has seismically vulnerable levels, the damage due to seismic hazards such as tsunamis could threaten Bengkulu City [12]. Therefore, the evacuation process in the near coastal zone should be prioritised. In Bengkulu City, the Pantai Panjang Area is known as one of the developed areas. In addition, this area is very close to the coastline. The information related to the evacuation zone for this area is still limited.

Evacuating residents on a large scale is complicated and difficult, depending on using an efficient transportation system and an effective evacuation scheme [13]. Therefore, the analysis of the evacuation line should be carefully performed. A method called the four-step model is implemented in ZIN macrosimulation software [14]. The four-step model (4-stage modelling) is a model that is used to predict future transportation conditions for a particular area and condition. The parameters in this modelling consist of 4 parts, namely trip generation, trip distribution, mode selection, and traffic assignment, often known as 4-stage modelling, and are often used to solve transportation problems. According to Hardiansyah *et al.* [15] and Hardiansyah *et al.* [16], the four-step model method is an effective method for conducting research on the vulnerability of the road network due to the evacuation process of the Mount Merapi eruption disaster in Yogyakarta and this research produces a model that is close to actual conditions.

According to Kagho *et al.* [17], transportation planning presented a significant development in the 1950s in which the four-stage modelling is still relevant. The model provides transport planners with the representation of traffic flow, which can be used for future development. The classic four-step model does not capture how most travellers behave due to its nature of modelling aggregate data (space, time and travellers). Nevertheless, the use of the four-step model is still applicable to be implemented for road networks. Tang and Waters [18] mentioned that the four-step model should include exploring the problem, including issues and concerns, exploring and creating solutions and ideas, developing and examining alternatives, and feedback and evaluating alternative ways to solve the problem. In line with the step-by-step implementation of the model, the evaluation of every step should be carefully considered to ensure a better transportation plan [19].

In line with the benefit of the four-step model, the transportation plan for areas with high-risk natural disaster impact can be obtained by analysis conducted under the four-step model. For example, the study area in Bengkulu City discussed in this study (Fig. 1) is a tourist area where an open ocean and some facilities such as shopping malls and hotels are integrated. In addition, as previously elaborated, the general area is very vulnerable to undergoing seismic damage such as tsunamis and liquefaction. With limited access to evacuation during seismic disasters, the issue of how to mitigate people around is the main one. Therefore, the analysis under the four-step model must be crucial in helping to reduce the potential impact.

This paper presents a study of evaluation of the road vulnerability network during the evacuation process (A case study in Bengkulu City Coastal Area, Indonesia), with the main focus area being Pantai Panjang of Bengkulu City. The size/complexity of the study area is limited, in which only the network is composed of only 6 roads. However, regarding the importance of this area, it is very meaningful for the city's development to support economic and social aspects in the study area. In addition, the study area is categorised as one of the most vulnerable areas in Bengkulu City to the tsunami disaster. Therefore, this study is important to perform. This research focuses on implementing the four-step model in identifying the performance of the road network in coastal areas during a tsunami evacuation time. A study using the four-step model method would produce the most optimal evacuation route to support the movement of evacuees. With an optimal road network, evacuation during a disaster is expected to serve the movement of evacuees so that many lives can be saved, especially if a tsunami hazard attacks this area. This study is also a part of contributions to support the city development based on hazard mitigation.

2. Material and Method

2.1. Study Area

Figure 1 presents the layout of the study area. As presented in Fig. 1, the position of Pantai Panjang Zone is very close to the Indian Ocean. During the Bengkulu-Mentawai Earthquake, liquefaction spots and low-tide tsunamis are reported. This research was conducted on a road network in the Bencoolen Mall area (one of the biggest shopping centres in the coastal area of Bengkulu City), located in the Pantai Panjang Tourist Area, Bengkulu City. In this zone, there are several road networks. The road networks in the research scope include Pariwisata Road, Sedap Malam Road, and Putri Gading Cempaka Road. Geographically, the location of this research is at latitude 3°48'45" S and longitude 102°16'15"E.

In Fig. 2, the scenario of the evacuation line is also presented. The red indicates a scenario for an additional road network, and the blue indicates a scenario for increasing road capacity or enlarging the road width.

2.2. Transportation Modelling for Evacuation

Evacuation during disasters is important [20]. Therefore, the effort to model the transportation modelling for evacuation is also very important [21]. Punakivi and Hinkka [22] stated that the concept of transportation planning that has developed to date and is the most popular is the four-step transportation planning model (Four Step Model). The four models include the trip generation, trip distribution, mode choice, and trip assignment models.

Disaster disturbances such as tsunamis, floods, earthquakes, volcanic eruptions, etc., can affect travel on the road network. Modelling network performance in degraded conditions is focused on setting traffic routes rather than changing modes and choosing destinations or approaches with traffic management that involves choosing driver routes, so it is necessary to apply an evacuation transportation model based on road network performance to optimise the role of evacuation routes in serving evacuee [13].

Micari *et al.* [23] described the road network's performance by allocating each movement between zones to various routes most often used by someone moving from the origin zone to the destination zone. Thus, traffic flow on each road segment in the road network can be estimated—analysis of road performance using the conventional method, with the main parameter being the degree of saturation. The ideal condition on the highway is a condition where the value of the degree of saturation is less than or equal to 0.85. The value of the degree of saturation is influenced by volume and capacity. Capacity is defined as the maximum current through a given point. The basic equation for determining capacity is as follows:

$$C = C_0 \times F_{CW} \times F_{CSP} \times F_{CSF} \times F_{CCS} \tag{1}$$

where C is road capacity (light vehicle unit (lvu)/hour), C_O is base capacity (light vehicle unit/hour), F_{CW} is Road width adjustment factor, F_{CSP} is Directional separation adjustment factor, F_{CSF} is adjustment factor for side resistance and road/kerb, F_{CCS} is adjustment factor for city population.

The Ministry of Public Works of Indonesia [24] defines the degree of saturation as the ratio of current to capacity, which is used as the main factor in determining the performance level of intersections and roads with capacity problems. The equation for determining the degree of saturation is as follows:

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

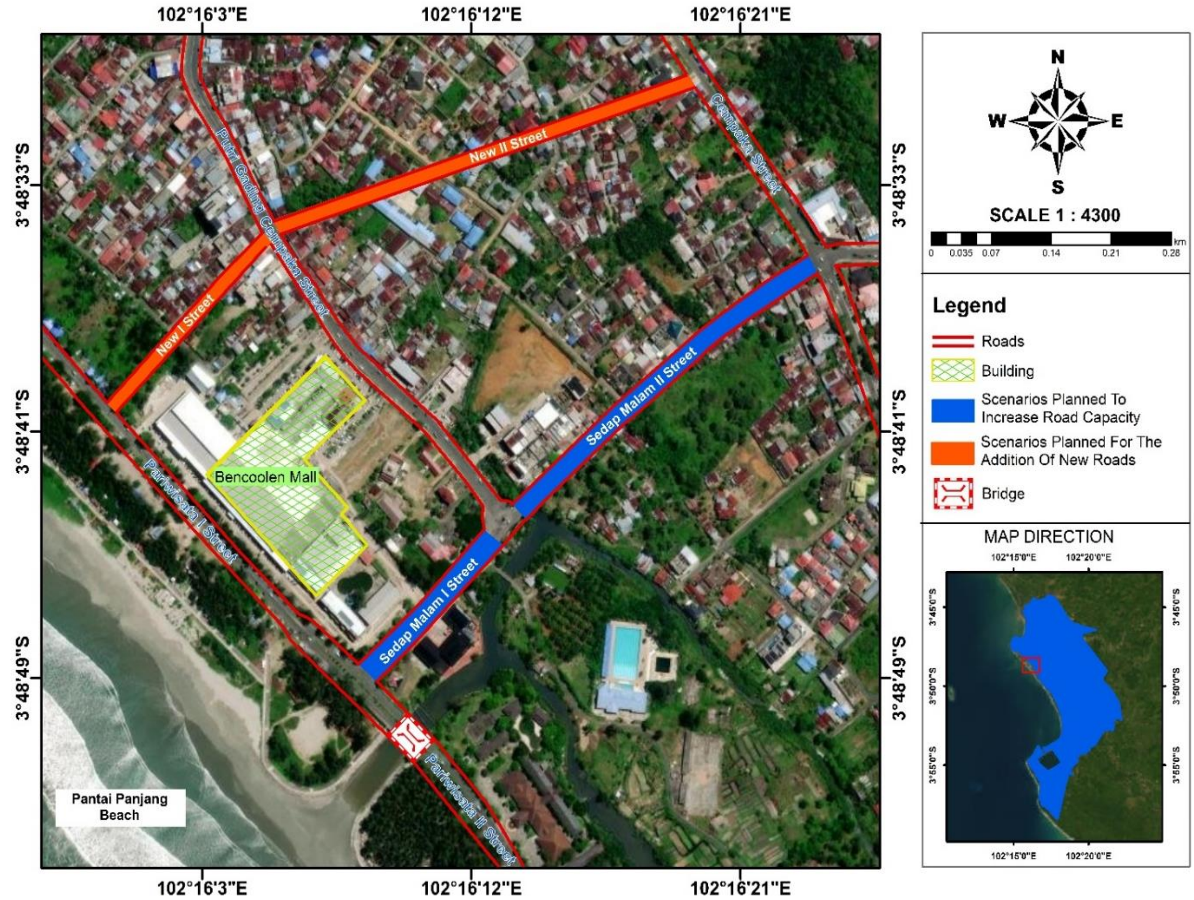

Fig. 1. The layout of the study area.

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where D_S is the degree of saturation, Q is total traffic flow (lvu/hour) and C is the capacity (lvu/hour).

Based on the US-Highway Capacity Manual [25], six classes exist for the degree of saturation or Volume Capacity Ratio (*VCR*). Class A for $0 \leq D_S < 0.20$. This reflects a condition of free traffic flow with high speed and low traffic volume. For $0.21 \leq D_S < 0.44$, it reflects a stable condition, but the operating speed is starting to be limited by traffic conditions. For $0.45 \leq D_S < 0{,}74$, It is a stable condition, but the vehicle's motion is controlled. For $0.75 \leq D_S < 0.84$, It is a condition where the current is near stable, and the speed can still be controlled. It is unstable for $0.85 \leq D_S < 1.00$; speed sometimes stalls, and demand is approaching capacity. For $D_S > 1$, it is a condition of forced flow, low speed, flow volume above capacity, and long queues (congestion).

Evacuation modelling usually has a study area with comprehensive coverage and involves many links and zones, so the scope of model development is included in the macroscopic category. Macroscopic models can assess network performance during an emergency disaster [15]. Trip distribution is the number of trips starting from a zone of origin that spreads to many destination zones or vice versa, the number of trips that come together to a destination zone that previously came from several origin zones. Transportation planners often use the movement matrix or Origin-Destination Matrix (MAT) to describe movement or travel patterns. Origin-Destination Matrix (MAT) is a two-dimensional matrix containing information about the magnitude of movement between zones within a particular area. Rows represent origin zones, and columns represent destination zones [26]. For long-term prediction, the estimated traffic volume is calculated using the growth method based on the value of vehicle growth. The traffic volume can be estimated for five years, ten years, and so on as desired [27]. The general equation used to calculate the estimated traffic volume using the growth rate method, according to Supranto [28], the equation for forecasting future traffic volumes is as follows:

$$P_n = P_0 \times (1+i)^n \tag{3}$$

P_n is the total traffic volume at the end of the year to-n, P_0 is the total daily traffic volume, i is the Vehicle growth rate, and n is the number of times (in years).

2.3. Network Vulnerability Index

According to Hardiansyah *et al.* [16], the traffic model to assess the performance of road networks due to natural disasters has been developed in the past. However, some researchers have investigated whether evacuees know the recommended routes to protected areas and whether they want to use them. This paper adopts a vulnerability index and identifies network links to improve by mapping them to a simple 'traffic light style' congestion scale.

The development of a model to identify the critical relationship of the road network with roads partially/entirely to natural disasters. The important factor to assess the existing condition during evacuation should be defined. Research produces a vulnerability index called the Network Vulnerability Index (NVI), which considers the ease of road repair based on the relative loss of capacity [16]. The vulnerability index equation is as follows:

$$INVE_F = \left[\frac{\left(\sum_{i=1}^{|X|} F_E\right) - \left(\sum_{i=1}^{|X|} F_D\right)}{\left(\sum_{i=1}^{|X|} F_D\right)} \right] \tag{4}$$

$INVE_F$ is the network vulnerability index, FE is the evacuation volume, and F_D is the daily volume.

2.4. Modelling Framework

The research framework in this study is presented in Figure 2. This study is initiated by capturing the evacuation issue during the hazardous tsunami in Bengkulu City, especially in the Pantai Panjang Area. Furthermore, data collection is performed. There are two kinds of data collected in this study. The first one is primary data. Information on the maximum vehicle flow at peak hours, the geometry of the road, and questionnaire from visitors in the Pantai Panjang Area is categorised as primary data. For secondary data, information on the flow of entrance and exit for vehicles in Pantai Panjang, Bengkulu City population, and the growth of vehicle data is categorised as secondary data.

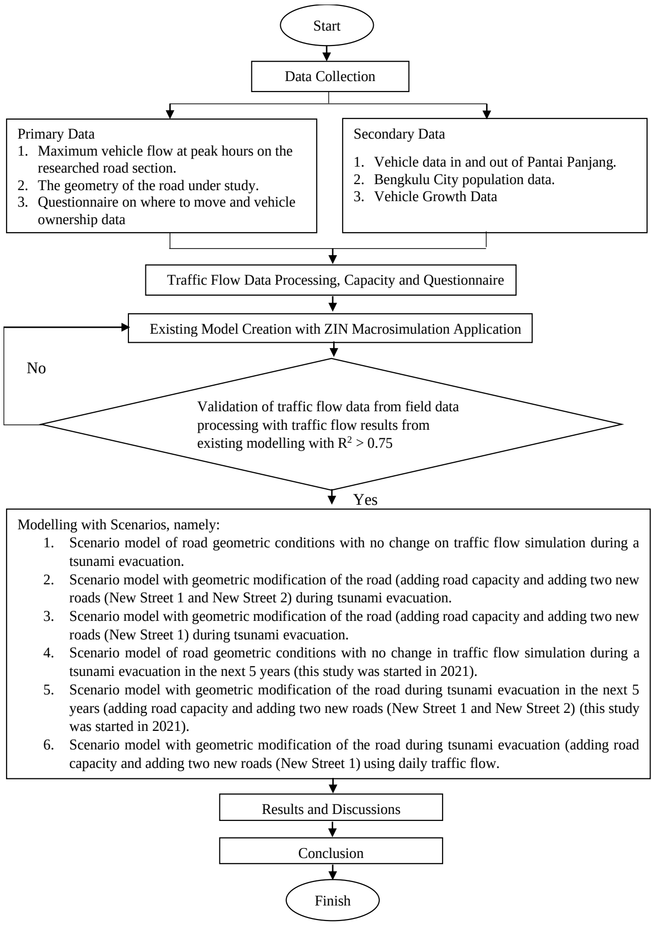

Fig. 2. Research flowchart.

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After data collection, data recapitulation, data processing, and analysis of questionnaire data are conducted. For the data questionnaire, the tendency of scenarios recommended by visitors based on in-depth interviews is also presented. The transportation model using the steps model is generated and validated based on the actual condition. This study compares volume from the model and volume based on actual conditions. The coefficient of determination (R^2) of more than 0.75 assumes that the model is reliable and can be implemented for scenario models. There are six scenarios considered in the simulation, as follows:

1. Scenario 1 considers road geometric conditions without changing traffic flow simulation (existing condition) during a tsunami evacuation.
2. Scenario 2 considers geometric modification of the road (adding road capacity and two new roads, i.e., New Street 1 and New Street 2) during tsunami evacuation.
3. Scenario 3 considers the geometric modification of the road (adding road capacity and one new road. i.e., New Street 1) during tsunami evacuation.
4. Scenario 4 considers existing road geometric conditions with changing traffic flow simulation (from 2021 to 2026) during a tsunami evacuation.
5. Scenario 5 considers geometric modification of the road (adding road capacity and two new roads, i.e., New Street 1 and New Street 2) with changing traffic flow simulation from 2021 to 2026, during a tsunami evacuation during tsunami evacuation.
6. Scenario 6 considers the geometric modification of the road (adding road capacity and one new road. i.e., New Street 1) with changing traffic flow simulation from 2021 to 2026, during a tsunami evacuation

Since evacuation during disasters is significantly related to the capacity of the road and degree of saturation, The simulation results are collected and analysed in terms of the degree of saturation and capacity. From the analysis results, this study's conclusion is formulated.

3. Results and Discussion

3.1. Results of the Questionnaire

Before the analysis, a questionnaire survey is conducted to obtain road selection and duration information. Figure 3 presents the situation map in the Pantai Panjang Region. In Figure 3, Zone A is known as Recreation Park, where the refreshing activity near the coastline is generally done. In this zone, several playing grounds and traditional shops exist. Zone B is also known as the traditional shops' zone. There is a semi-modern shopping mall called Bencoolen Mall, indicated as Zone C. In Zone C, the mass concentration in terms of the visitor is centralised. This shopping mall 0is operated every day from 09.00 am to 10.00 pm.

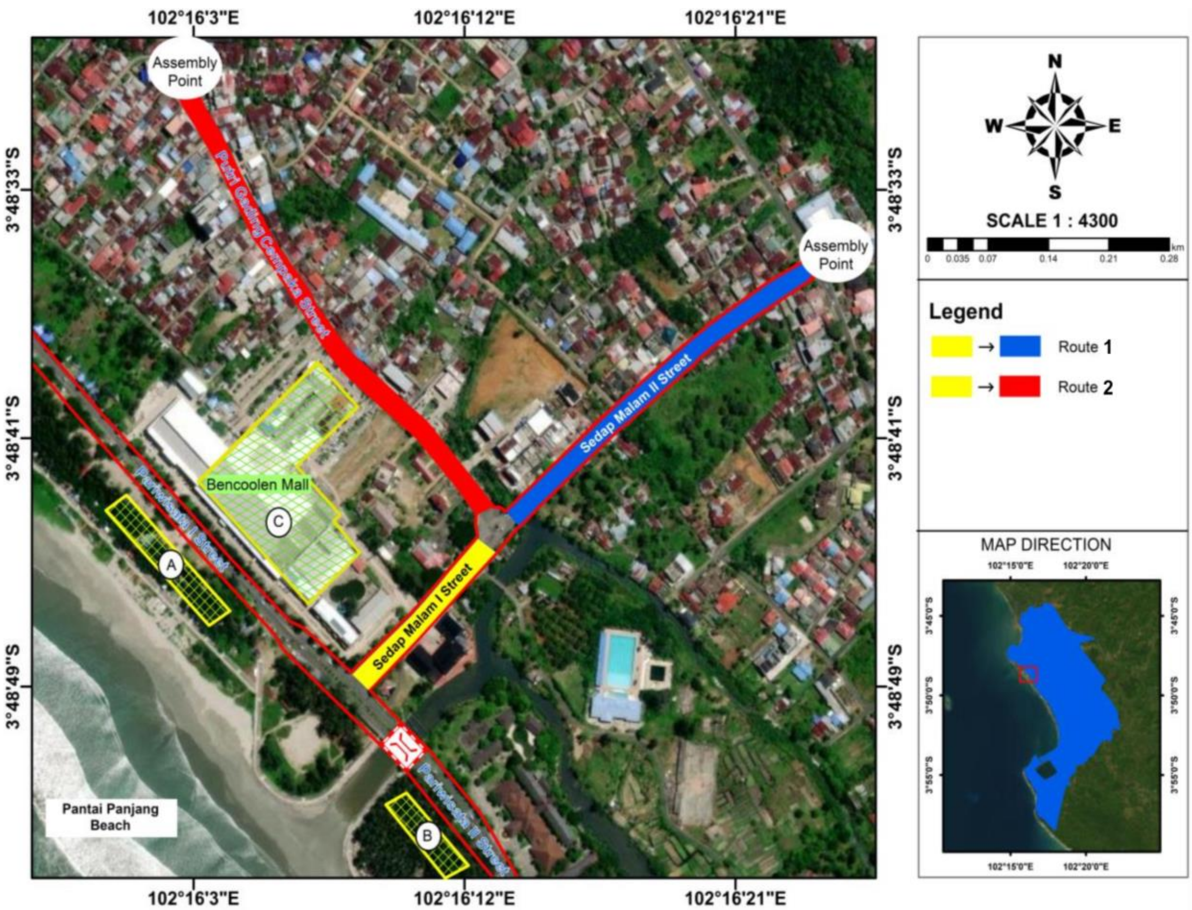

Fig. 3. Evacuation route options based on questionnaire.

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The questionnaire results for 181 respondents show that 161 respondents (84%) and 30 selected Route 1 and 2, respectively. According to the results, about 70% of respondents mention that the evacuation from Zone 1 to the assembly point is about 1 to 10 minutes. About 25% of respondents revealed that the prediction for evacuation time from this distance is 11 to 20 minutes. 4% of respondents suggested the evacuation time is about 21 to 31 minutes. About 1% of respondents believe that the evacuation time for Route 1 is more than 31 minutes. For Zone B to the assembly points, 61% of respondents said the evacuation time required is 1 to 10 minutes, 32% of respondents said the time is about 11 to 20 minutes, 6% of respondents mentioned 21 to 30 minutes, and 1% of respondents predicted the time of more than 30 minutes. Generally, based on the analysis, about 53% of respondents choose Route 1 from Zone C to assembly points, and about 47% choose Route 2. The prediction of evacuation time for this condition is about 1-10 minutes (76% of respondents), 11 to 20 minutes (20% of respondents), 21 to 30 minutes (2% of respondents), and more than 30 minutes (2% of respondents).

3.2. Model Validation

Model validation is conducted in this study to ensure that the generated model works accordingly. The concept of model validation implemented in this study is to compare the existing. Observation results and model prediction results are compared to each other. Using the least square method, the tendency of the model is presented. The model is reliable if the comparison shows a coefficient of determination (R^2) of more than 075.

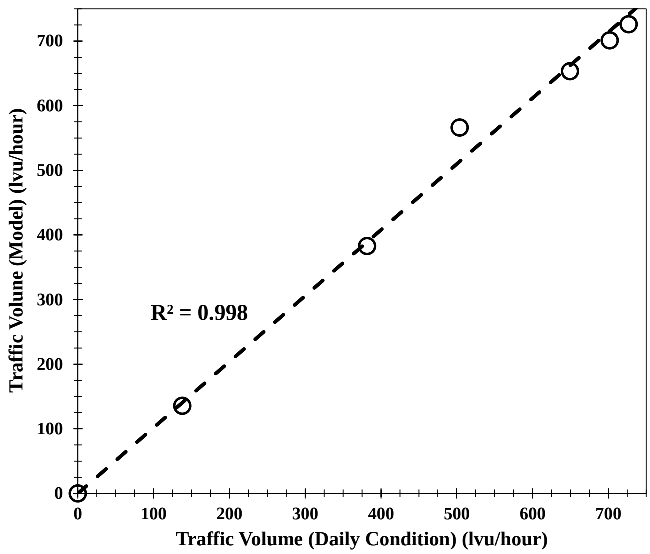


Fig. 4. Traffic volume comparison.

Figure 4 shows the model validation in this study. It can be observed that there are six roads surrounding the study area (Fig. 1). The first road is Cempaka Street, the second is Putri Gading Cempaka Street, the third is Sedap Malam II Street, the fourth is Sedap Malam I Street, and the fifth is Pariwisata I Street. The last one is Pariwisata II Street. On all those streets, the observation of daily traffic volume is conducted. Furthermore, the traffic volume predicted from the model is presented. Both volumes are then compared for each observed and analysed street. From Fig. 4, it can be observed that the traffic volume from the observation and traffic volume from the model is generally consistent with each other. The coefficient of determination or R^2 for the comparison data is about 0.998. The results show 99.8% of the volume of vehicles passing on the researched road segment based on the existing conditions in the field, and the existing modelling is valid. It also strengthens the assumption that the model is reliable enough to be implemented in this study because R^2 for the comparison is more than 0.75. The detail of data compared for Fig. 4 is presented in Table 1.

Table 1. Daily and predicted traffic volumes.

Streets	Daily Traffic Volume (light vehicle unit/hour)	Predicted Traffic Volume (light vehicle unit/hour)
Pariwisata I Street	727.00	726.13
Pariwisata II Street	702.00	701.17
Sedap Malam I Street	449.60	653.30
Sedap Malam II Street	504.00	566.13
Putri Gading Cempaka Street	381.80	382.95
Cempaka Street	138.00	135.55

3.3. Road Network Performance Results Analysis

As elaborated in the previous section, the analysis of the degree of saturation for each scenario is considered in this study. Road performance is defined to be poor when the degree of saturation is more than 0.84. The degree of saturation compilation for all considered scenarios and the existing condition is shown in Fig. 5.

Based on field observation, it can be observed that, generally, the degree of saturation on each road segment is observed to vary from 0.06 to 0.21. It indicates that the performance of the road is relatively good. For Scenario 1, when there is a hazard, for example, a tsunami, the degree of saturation increases from 0.2 to 0.64. Sedap Malam I and Sedap Malam II Streets have undergone a significant increase. Therefore, for long-term service of road performance, the modification of traffic situation and road geometry and the new road construction in Pantai Panjang Zone could be implemented to decrease the degree of saturation that could be increased in the future.

For Scenario 2, i.e., there is a modification on road geometric and adding two new roads. The effect of adding road capacity and adding two new roads using daily traffic flow with the assumption that a tsunami hits the area shows that the degree of saturation decreases with a variation of 0.14 to 0.24. It indicates that the modification and two new roads could well work to distribute the traffic volume during evacuation.

For Scenario 3, the geometric modification and addition of New Road 1 could improve the performance of the road during evacuation by decreasing the degree of saturation and traffic flow during evacuation. Under this scenario, the degree of saturation is observed to vary from

0.19 to 0.29. The results of the first three scenarios indicate that the additional roads could improve the degree of saturation. The results also show that two roads, Sedap Malam I and Sedap Malam II, tend to have higher saturation. These two roads are inline, the main access road near the Pantai Panjang Zone.

The performance prediction in the next five years is conducted to observe the performance of models and scenarios of traffic conditions in this study. It has been known that the growth rate of vehicles in Bengkulu City is about 5% for light vehicles and 2% for motorbikes. Therefore, traffic volume prediction in 2026 could be predicted based on these growth rates. Furthermore, Scenarios 4, 5, and 6 are conducted by considering the growth rate.

For Scenario 4, it can be observed that under the existing condition with traffic volume in the next five years, the degree of saturation of each road segment is observed to vary from 0.3 to 0.68. There is an increase in the degree of saturation in which both Sedap Malam I and Sedap Malam 2 streets still have a higher degree of saturation.

For Scenario 5, the additional two new roads and geometric modifications could serve good road performance during evacuation in the study area in the next five years. Based on the model simulation, it can be observed that the degree of saturation varies from 0.24 to 0.44, with a higher degree of saturation indicated by Sedam Malam I and Sedap Malam II roads.

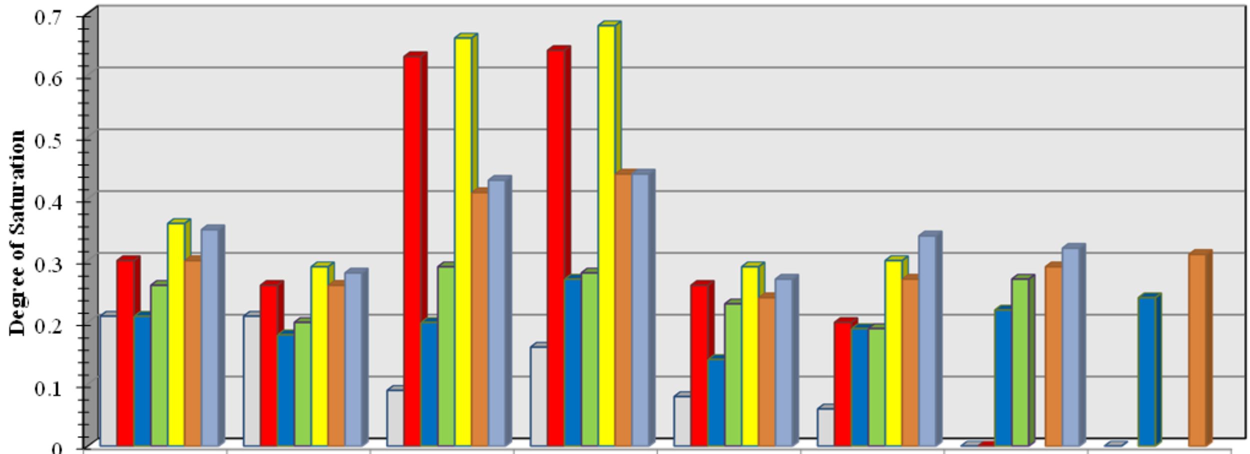
For Scenario 6, the additional new road, i.e., New Road I, shows that the degree of saturation on each segment is observed to vary from 0.32 to 0.44. Similar to all previous scenarios, Sedap Malam I and Sedam Malam II show higher saturation.

The results show that the geometric modifications and additional roads could serve a sound road performance during evacuation. In the next five years, the performance of the road is also still reliable. However, the quality of road construction is also needed to improve to support road performance. A good road performance could ensure a better evacuation process.

3.4. Analysis of Road Vulnerability Index to Tsunami Disaster Evacuation

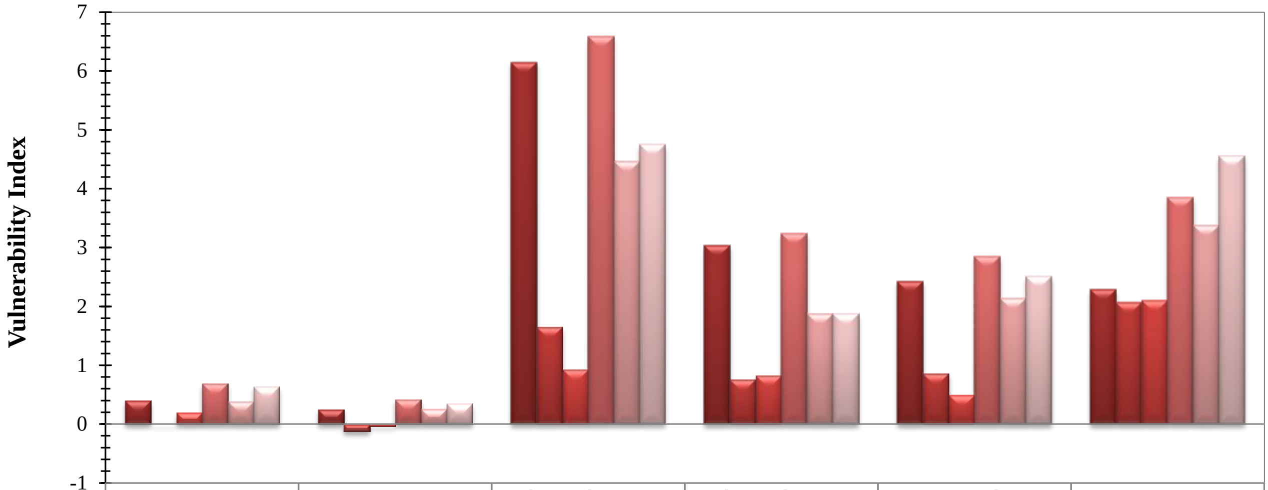
The analysis of the vulnerability index is conducted in this study to assess road vulnerability. The vulnerability index is significantly related to the evacuation volume and daily volume. A positive value of the vulnerability index indicates that the road is vulnerable to tsunami disasters. This is because, during the evacuation process, the road density becomes more extensive, making the users on the road more vulnerable to the impact of hazards—the results of the road vulnerability index to the disaster during the evacuation are presented in Fig. 6.

Figure 6 shows that, based on the simulation results, all roads are vulnerable to disasters for Scenarios 1, 4, 5, and 6. Those roads have a positive value on one vulnerability index. For Scenario 2, several roads, namely Pariwisata I Street, Putri Gading Cempaka Street, and Cempaka Street, are vulnerable to hazard impact. These roads also tend to have a positive value of the vulnerability index. Another two roads, Pariwisata I Street and Pariwisata Street have a negative vulnerability index value. It indicates that these roads are not vulnerable to hazard impact during evacuation.



	Pariwisata I Street	Pariwisata II Street	Sedap Malam I Street	Sedap Malam II Street	Putri Gading Cempaka Street	Cempaka Street	New Street I	New Street II
Field Survey	0.21	0.21	0.09	0.16	0.08	0.06	0	0
Scenario 1	0.3	0.26	0.63	0.64	0.26	0.2	0	
Scenario 2	0.21	0.18	0.2	0.27	0.14	0.19	0.22	0.24
Scenario 3	0.26	0.2	0.29	0.28	0.23	0.19	0.27	
Scenario 4	0.36	0.29	0.66	0.68	0.29	0.3		
Scenario 5	0.3	0.26	0.41	0.44	0.24	0.27	0.29	0.31
Scenario 6	0.35	0.28	0.43	0.44	0.27	0.34	0.32	

Fig. 5. Graph of the degree of saturation.



	Pariwisata Street I	Pariwisata Street II	Sedap Malam Street I	Sedap Malam Street II	Putri Gading Cempaka Street	Cempaka Street
Scenario 1	0.4	0.25	6.15	3.04	2.43	2.29
Scenario 2	-0.01	-0.12	1.65	0.76	0.86	2.07
Scenario3	0.2	-0.03	0.93	0.83	0.5	2.1
Scenario 4	0.69	0.42	6.59	3.24	2.85	3.85
Scenario 5	0.39	0.26	4.46	1.87	2.14	3.38
Scenario 6	0.64	0.35	4.75	1.87	2.51	4.56

Fig. 6. Graph of the vulnerability index of road.

For Scenario 3, Several roads, including Pariwisata I, Sedap Malam I, Sedap Malam II Street, Putri Gading Cempaka Street, and Cempaka Street, have a positive value of the vulnerability index. It indicates that the road is also vulnerable to the impact of hazards during evacuation. Only Pariwisata II Street does not have a positive value on the vulnerability index. It indicates that the road is not vulnerable to hazard impact during the evacuation.

4. Conclusion

This study analyses the road performance network during the hazard evacuation in Pantai Panjang Area, Bengkulu. The four-step model is performed to simulate several scenarios that could happen in the study area. Several concluding remarks can be drawn as follows:

- The questionnaire results show that respondents chose Route 1, namely Sedap Malam Street I and Sedap Malam Street II, as evacuation routes during the tsunami disaster.
- Based on the modelling results, the ZIN Microsimulation software can model the traffic flow distribution with a comparison to the traffic flow from the survey results in the field of $R^2 = 0.928$. The results show 92.8% of the number of vehicle volumes on the studied road segment based on the existing conditions in the field, and the existing modelling is valid.
- The modelling results from all scenarios with the best road service level are Scenarios 2 and 5, namely by adding road capacity and making two new roads.
- In Scenarios 1, 4, 5, and 6, all roads are Vulnerable to tsunami disasters. In Scenario 2, there are two roads, Pariwisata Street I and Pariwisata Street II, which are not vulnerable. In scenario 3, one road, namely Pariwisata Street II, is not vulnerable because the vulnerability index value is negative.

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