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Original Article

Use of integrated transportation system approach to develop road network and bridge management strategy

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Abstract

The growth of the social-economic structure in a region is influenced by the performance of the transportation system, measured by the levels of accessibility and mobility. Unfortunately, there is no adequate model would help decide the prioritization in handling road and/or bridge damage, based on the degree of damage, physical connectedness, and functional connectivity. This study seeks to address that lack. The functional condition of the road is determined and quantified by the Surface Distress Index (SDI), while the type of preservation is determined based on the SDI and the functional connectivity. The functional condition of the bridge is determined using the Bridge Management System (BMS) method. The levels of damage to roads and bridges were found to be 26% and 23%, respectively. The prioritization for handling is given to the main connecting roads in areas that have the greatest contribution to the economic structure, and similar goes for the bridges. Repairing potholes and overlaying are the two most common types of road preservation, whereas guard rail replacement, overlaying of bridge floors, and building runoff bridges are the most common types of bridge maintenance.

Keywords: accessibility index, integrated land use and transportation, physical and functional connectivity, surface distress index

1. Introduction

The success of sustainable development could be measured by the increasing values of the economic and social structures, based on their contributions to the gross domestic product. In this regard, the type, scale and density of economic activity are influenced by the availability and/or the quality of transportation infrastructure, and *vice versa* (da Costa *et al*., 2019). Physical and functional connectivity are the determinants of levels of accessibility and mobility within and between regions (da Costa, 2016), measured using accessibility index.

East Sumba Regency is located on Sumba Island, one of the 4 biggest islands in East Nusa Tenggara Province. Statistical data show that their contributions to Gross Regional Domestic Product/GRDP come dominantly from agricultural, trade, and (government or private) service sectors (Badan Pusat Statistik, 2021). Theoretically, the shortest path, the shortest time of travel, or the lowest transport cost, is used to describe the level of accessibility. These are influenced by the functional condition of roads and bridges as well as the characteristics of commodities transported. Therefore, accessibility and mobility within or between regions are crucial issues. The purpose of this study was to identify the current level of accessibility and mobility, and to recommend the appropriate type of road and bridge preservation so as to improve the levels of accessibility and mobility.

Surveys of the functional condition of roads and bridges are intended to improve the quality, and while those data are updated annually, not every damaged road or bridge can be handled promptly or proportionally, due to the following aspects: 1) high dependency on getting preservation cost allocated by the Center Government at Jakarta; and 2) limited or lacking local human resources. These may occur due to: 1) unavailable technical guidelines to prioritize roads or bridges; and 2) inadequate insights into how to increase the accessibility or mobility level, based on the land use and transportation integration system. Therefore, the results of this study are intended to serve as a basis in the determination of a

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road and bridge management strategy.

2. Materials and Methods

2.1 Research variables

In order to address the research objectives, it is necessary to analyze the level of damage to roads and bridges based on: 1) functional value of road pavements; 2) geotagging photos (coordinates and road or bridge element's conditions); 3) name and location distribution of road segment; 4) starting point and end point of each road; 5) the names of bridges; and 6) leading economic sector in each sub-district.

The condition of road damage per 200 meters of road length is used as the basis for determining the level of road damage, while geotagging photos are used to show such damage conditions. These would be used to determine the level of damage and the type of preservation needed. Additionally, information about the leading economic sectors is needed for an analysis of accessibility and mobility within and between regions. Subsequently, the value of functional condition of roads is used to determine the level of damage using accessibility index (Equation 1). An index close to 1.0 means that accessibility is in very poor condition.

$$\text{Accessibility Index (AI)} = \frac{\Sigma P_{rl}}{T_{rl}} \quad (1)$$

P_{rl} = total road length within poor categories (km)
T_{rl} = total road length (km)

2.2 Data collection

2.2.1 Survey of road surface distress and inventory of bridge condition

An Android based software application, namely geo-tracker, was used to determine the position of each observation location, to make data retrieval easier. The data on the functional condition of a road was compiled, and the Surface Distress Index (SDI) was calculated (Setiadji, Supriyonno, & Purwanto, 2019). The assessment criteria for each type of failure are summarized in Table 1. The greater the value of SDI, the worse is condition of the road segment.

Data on the damage level in conditions of bridges were collected using a bridge inventory form, and assessed using the Bridge Management System (BMS) method (CV. Graha Mandiri Consultan, 2022; Pratama, Vaza, Irawan, & Halim, 2015). The score for damage in each bridge's structural elements was then summarized to an average level of damage, shown in Table 2 (CV. GMC, 2022).

This type of bridge inventory survey was used because it offers fast assessment based on the surveyor's visual assessment. The visual investigation was preferred due to budget constraints in the data collection phase, as a consequence of geographical and topographical characteristics.

As the assessment and scoring criteria for structural elements were in an 0-5 scale, which are associated with appropriate types of bridge preservation based on functional condition before conducting observations, each surveyor was instructed regarding how to recognize the type and scale of damage, as well as how to score such conditions. In the scoring, 0 = no damage (new bridge), 1 = light damage (hair crack on pavement/bridge floor, corrosion at hand railing or floor beam, etc.), 2 = requires monitoring and maintenance in the near future (excessive waterlogging or sedimentation of bridge's floor or inlet drain, initial scouring or erosion on foundation, expansion joint, or deterioration on hand railing), 3 = immediate action (pothole on pavement, broken headwall or wing wall, missing elements of hand railing), 4 = critical condition (damage on pier or pile cap, excessive vibration on bridge floor, heavy damage on foundation elements, pothole on two-way lane of bridge floor), and 5 = dysfunctional elements (heavy damage on floor, missing hand railing, the bridge cannot be used safely).

Table 1. Road condition assessment criteria

Type of failure	Scoring of failure condition			Remark
	Weight	Condition	SDI value	
Crack area	1	None	SDI_1 = 0	ΣSDI <50 = Good condition
	2	≤10%	SDI_1 = 5	50 > ΣSDI < 100 = Light damage
	3	10-30%	SDI_1 = 20	100 > Σ SDI < 500 = Medium damage
	4	>30%	SDI_1 = 40	ΣSDI > 150 = Heavy damage
Crack width	1	None	SDI_2 = SDI_1	
	2	Smooth <1mm	SDI_2 = SDI_1	
	3	Medium 1-3 mm	SDI_2 = SDI_1	
	4	Wide >3mm	SDI_2 = SDI_1 x 2	
Number of potholes	1	None	SDI_3 = SDI_3	
	2	>10/100 m	SDI_3 = SDI_2 + 15	
	3	10-50/100 m	SDI_3 = SDI_2 + 75	
	4	>50/100 m	SDI_3 = SDI_2 + 225	
Wheel path	1	None	SDI_4 = SDI_3	
	2	> 1 cm (X = 0.5)	SDI_4 = SDI_3 + 5X	
	3	1-3 cm (X = 2)	SDI_4 = SDI_3 + 5X	
	4	> 3 cm (X = 4)	SDI_4 = SDI_3 + 5X	

Source: Final report of road network database of East Sumba Regency, 2022

2.3 Mapping

Damage conditions could be easily displayed on the map using ArcGIS application because of geotagging of photos. The information displayed in the road and bridge condition map consisted of coordinates of the location, photos of the damage, and name of the road or bridge.

The following points then could be identified from it: 1) interconnected roads (travel chains) between sub-districts that are the centers of leading sector activities; 2) the number of bridges or river crossing areas on the main connecting road between the centers of activity. This information could be used to determine priorities in preservation actions for roads or bridges (Irawan, Ismiyati, Pudjianto, 2016; Sudradjat, Djakfar, Zaika, 2015).

3. Results and Discussion

3.1 Road functional condition

Table 3 shows that from a total of 160 roads (103.13 Km) in the subdistrict of Waingapu City (PT. Kencana Adya Daniswara, 2022), the fraction of damaged road is around 5.77% (approximately 5.95 Km). This is relatively small, but must be repaired immediately because the rate of increase in potholes as damage grows exponentially with the time delay. The longer that the damage treatment is delayer, the higher the damage rate (Munggarani & Wibowo, 2017). The availability of a budget must be considered when prioritizing programs. For example, small potholes might be patched with concrete, or even with compacted limestone, etc.

Similar situations and necessities also occur in a number of main connecting roads between subdistricts that have been the main centers of economic activities (Table 4). The modified data were taken from the Final Report of Road Network Database of East Sumba Regency (PT. KAD, 2022). At least 7 subdistricts must receive priority attention in the repairs, because the primary connecting road has sustained damage for up to 24.62%. The damage fell under the category of severe damage, and prevented access to all but four-wheel drive (FWD) vehicles. The mountainous geography worsens the consequences of a damaged road even further (BPS, 2021).

3.2 Functional conditions of bridges

According to Table 5, taken from the final database report of road functional conditions in East Sumba Regency (PT. KAD, 2022), it is known that the majority of the bridges have varied degrees of damage, in the categories light (79%), moderate (4%), and heavy (3%) damage.

3.3 Damaged road and bridge distribution by location

Mapping the locations of damaged road segments and bridges was done, and Figure 1 shows the locations of damaged bridges on the main connecting road between Haharu subdistrict (center of fisheries activity) and the National Road, supported with visual proof of the kinds of damage.

Table 2. Bridge condition assessment criteria

Name of bridge	Length (m)	Carriage width (m)	Scoring* (0-5)					Total score	Average	Level of damage*
			Upper structure			Lower structure				
			Type of construction	Floor condition	Guard rail	Pile cap	Column			
			0-5	0-5	0-5	0-5	0-5	0-25	0-5	

* 0= none, 1= light damage, 2= requires maintenance, 3= immediate action, 4= critical condition, 5= dysfunctional elements
Source: Final report of road network database of East Sumba Regency, 2022

Table 3. Recapitulation of functional conditions

Number or Link	Length (Km)	Type of pavement					Functional condition							
		Hot rolled sheet	Penetration asphalt	Concrete asphalt	Telford/ Gravel	Soil	Good		Medium		Light damage		Heavy damage	
							Km	%	Km	%	Km	%	Km	%
160	103.130	79.890	21.060	0.000	1.315	0.030	86.940	84.301	10.170	9.861	1.950	1.891	4.000	3.879

Source: Modified data taken from the final report of Road Network Database of East Sumba Regency, 2022

Table 4. Recapitulation of functional conditions of the main connecting roads

Number of link	Number of districts	Length (Km)	Type of pavement					Functional condition							
			Hot rolled sheet	Penetration asphalt	Concrete asphalt	Telford/ Gravel	Soil	Good		Medium		Light damage		Heavy damage	
								Km	%	Km	%	Km	%	Km	%
79	7	107.43	62.105	61.543	0	7.217	0.03	73.09	68.035	7.885	7.34	3.28	3.05	23.175	21.572

Source: Modified data taken from the final report of Road Network Database of East Sumba Regency, 2022

Table 5. Recapitulation of the functional conditions of bridges

No	District	Bridge condition (Number)				Total number of bridge
		Light damage	Medium damage	Heavy damage	Good	
1	Haharu	7			1	8
2	Kahaung Eti	2	1	1	1	5
3	Kambata Mapabuhang	1				1
4	Kambera	5				5
5	Kanatang	10			8	18
6	Katalahamulingu	6				6
7	Kota Waingapu	5			2	7
8	Kuta	1				1
9	Lewa	3		1	3	7
10	Lewa Tidahu	15				15
11	Mahu	7		1	2	10
12	Matawai Lapau	12				12
13	Ngadungala	3	2			5
14	Paberawai	3				3
15	Padanjara	1				1
16	Pahungalodu	8			1	9
17	Pandawai	9		1		10
18	Rindi	7	1	1		9
19	Rindi-Pahungalodu				1	1
20	Tabundung	9	2			11
21	Umalulu	1			1	2
	Number	115	6	5	20	146
	Percentage	79%	4%	3%	14%	100%

Source: Final report of Road Network Database of East Sumba Regency, 2022

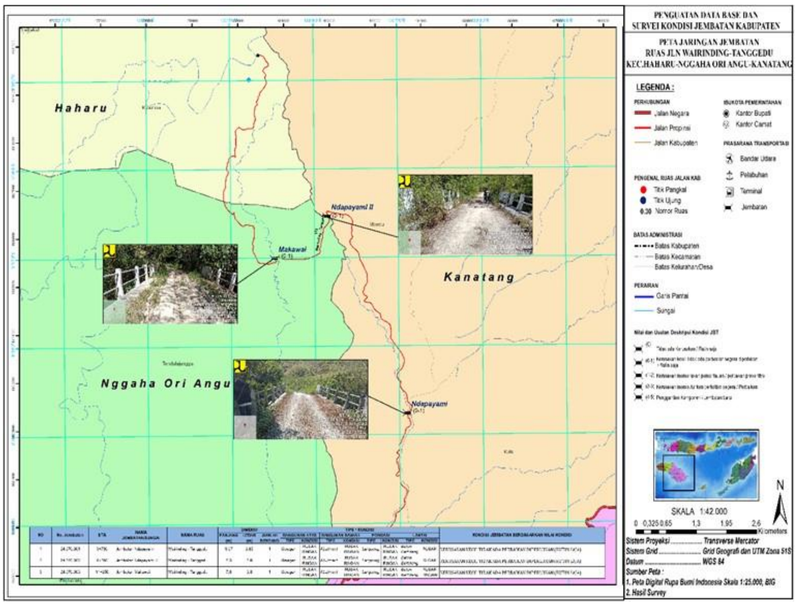

Figure 1. Example of a map showing damaged bridge locations

3.4 Land use and road network characteristics

The wetland agriculture locations in Lewa, Nggaha Ori Angu dan Lewa Tidahu districts are connected by National arterial road that crosses the East Sumba area from Central Sumba in a nearly straight line (Figure 2). The road network continues to encircle the southern region via Ngadu Ngala – Karera – Pinu Pahar – Tabundung – Katala Hamu Linggu. From Ngadu Ngala this arterial road is also connected to Waingapu City via the North route. Thus, the main pattern of the road network is basically a ring-radial type. Waingapu City is the main activity center served by a network of national roads and provincial roads, while for provincial road network services and district roads, the midpoint regions are Ngadu Ngala, Karera, Matawai La Pawu and Peberiwai, and Mahu as can also be seen in Figure 2.

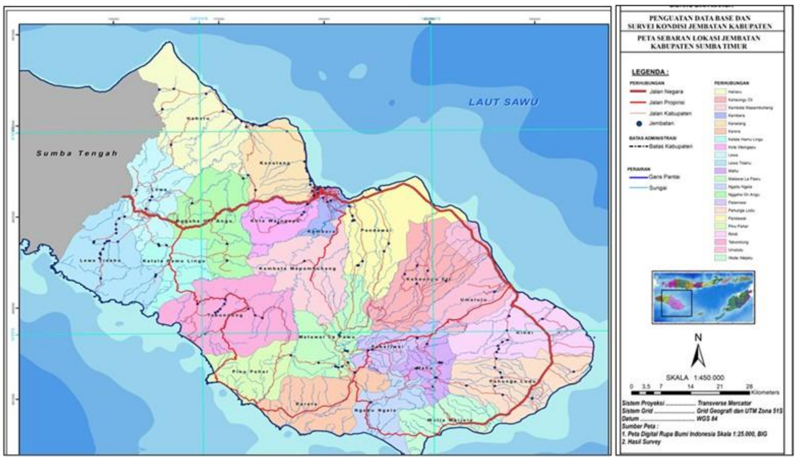

Figure 2. Locations of damaged bridges

However, Tables 3 and 4 indicate that the accessibility indexes of road network on Waingapu City, and the Main Connecting Roads within the largest GRDP contributor zones are 0.1563 and 0.3196 respectively. These were calculated using Equation 1, where the total lengths for district roads in Waingapu and the main connecting roads throughout the East Sumba Regency are 103.130 and 107.43 km, respectively, and the total road lengths in damage categories light, medium and heavy for those two clustered roads are 16.12 km and 34.34 km, respectively. Moreover, it was also found that total road damages in medium and heavy categories respectively contributed 13.74% and 28.91%. These strongly indicate those road segments as the main priorities for improvement.

Therefore, there should be good coordination between National – East Nusa Tenggara Province – Sumba Timur Regency's governments, when prioritizing maintenance as well as reconstruction programs. This is hard to materialize, because each government section has its own regional development intentions, described in regional spatial planning (these were produced not only by different planner consultants, but also at different times), particularly in the structural land use planning, depending on the physical, socio-economic, and environmental characteristics.

3.5 Road and bridge management strategy

Table 5 shows that the damaged bridge locations were spread over 7 subdistricts out of a total of 22 subdistricts. In addition, the leading economic sector is dominated by agricultural as well as trade and services sectors (BPS, 2021). Figure 2 above confirms this, so that the steadiness of having functional roads and bridges is an absolute necessity. Understandably, compiling recommendations for road and bridge preservation includes considering the level of accessibility and mobility within and between these areas.

Accessibility is a measure of the ease or difficulty of achieving a travel destination. It can be measured based on three main issues, namely travel distance, time, and cost (Tamin, 2000). Its level is influenced by the functionality of the roads and bridges, serving as functional units of travel service. Mobility is a measure of the ease of travel, measured based on the availability to, or ability of vehicles to pass through roads and bridges in a travel route (Tamin, 2000). Thus, mobility describes aspects of functional connectivity where the availability of roads and bridges allows the safe and smooth traffic of people and goods (Hasan & Kim, 2016). In this regard, damaged existing roads and bridges, including conditions at river crossings that have not been equipped with bridges, are major disturbing factors. These have an impact on the difficulty of traveling, particularly in the rainy season. They can directly impact smoothness, frequency, and volume of travel between regions (Kementrian Pekerjaan Umum dan Perumahan Rakyat, 2018). Furthermore, they will determine the logistics costs that partly determine the prices of commodities in retail (Wirabrata & Silalahi, 2012). This is why the levels of accessibility and mobility are the main indicators adopted in the trade sector.

On the other hand, intra- and inter-regional physical connectivity also have an impact on the socio-economic structure (Angelina & Wahyuni, 2019). There are always customary rites ongoing in the Sumba mainland, including marriages, funerals, and births. Due to the slaughter of traditional animals (buffaloes, cows, or pigs) during each traditional event, these social activities also have economic consequences. Additionally, there is close brotherhood between the tribes (Soeriadiredja, 2016), so that traditional events and their accompanying socio-economic impacts, in turn, have an impact on the attractiveness of cultural tourism trips to the island, which is full of cultural richness.

The recommendations for the management of bridges and road networks are based on the following considerations:

1. Physical connectivity is assessed based on the structure and pattern of the existing road network. As the main pattern of arterial road network is a combination between straight line and ring-radial patterns, all the road links connected with strategic subdistricts are the main roads that need high priority of handling. Unfortunately, the survey findings also reveal that many rivers still intersect connection routes but lack bridges.

The key crossing locations are as follows:

a. Laiwolang-Pahulu Bandil Road Link

Figure 3. Road link of Laiwolang-Pahulubandil STA 0+600, subdistrict of Matawai La Pawu

b. Kabanda – Langgai Road Link

Figure 4. Road link of Kabanda - Langgai STA 5.800, subdistrict of Ngadu Ngala

Crossings are also found in the road links of Melahar – Ramuk, Lailungi – Ramuk, and Watumbaka – Meurumba. Since the riverbeds at these crossing locations are generally shallow and flat, a drift bridge seems the appropriate type of bridge (Kementrian Pekerjaan Umum dan Perumahan Rakyat, 2021b). This type of run-off bridge is reasonably priced yet still functional enough to move vehicles throughout the rainy part of the year (KPUPR, 2021a). These might increase the accessibility and mobility because the service is robust throughout the year and in any case can shorten the travel time by about 10 - 30 minutes.

2. Functional connectivity assessed based on the connectivity of leading sector activities.

The sectors are dominated by the agriculture, trade, construction services, and other governmental and private services. The largest rice-producing areas are concentrated in the West, namely in the subdistricts of Lewa, Nggahu Ori Angu and Lewa Tidahu (more than 5 tons/year, the highest is in Lewa with around 8.4 tons/year). The largest upland rice producing areas (> 0.5 tons/year) are spread from the middle to the eastern tip of East Sumba Regency producing around 1.9 tons/year (BPS, 2021). Parts of this upland rice-producing area are crossed by National Roads (Wulla Waijelu and Rindi), and provincial roads (Ngadu Ngala, Karera, Paberiwai and Tabundung), while the rest is served by district roads (Mahu and Matawai La Pawu). In addition, the largest capture fisheries supporting areas (Kanatang, Waingapu City and Umalulu) (BPS, 2021) are all located on the National Road network so that the distribution can be carried out smoothly to anywhere. Thus, road and bridge preservation on the main roads must be prioritized so that a supply chain can be sustained.

3.6 Important and strategic findings

About 25% of the roads are in a damaged state. An immediate handling effort is required to reduce the road damage in nearby areas, according to KPUPR (2018); Trissiyana (2017). The locations of road damaged are sporadic, so that the priority is given to the main roads connecting centers of leading economic activities. The priority in bridge preservation should be similar. This is intended to minimize the travel time and cost, as well as to increase trip frequency. These in turn may increase the quantity of transported commodities.

The bridge damage classified as medium (bridges in the damage level of 2 and 3) is located on the main connecting road, where road and bridge preservation should be conducted immediately so that the level of damage would not increase and the level of accessibility could be maintained.

Depending on the rate at which the elements of roads and bridges are deteriorating, either regular or periodic maintenance is required. Thus, regular damage monitoring is necessary (KPUPR, 2018), at least once every 3 months. This suggests the necessity of a digital database system, so that the community can actively participate in reporting the changing situations in road or bridge damages, in real time throughout the year. This may reduce the cost of primary data collection. Such savings may be re-allocated to road and bridge preservation.

A number of river crossings have not been equipped with bridges.

As previously mentioned, the recommended type of bridge a drift bridge. The minimum drift width should be 3 m so that when crossing paths, 4-wheel and 2-wheel vehicles can pass through. The construction cost is relatively affordable but effectiveness is still quite high.

The use of culvert bridge types and masonry with special mortar is only recommended in river crossing areas where the discharge and velocity of river water flow are relatively small so that the potential for scouring and/or damage to construction in the area around the mouth of the culvert can be minimized (Qudus & Agustina, 2007). In addition, the number of culverts must also be taken into account against surface runoff water so that the potential for scouring due to water turbulence, as well as the effect of hydrostatic pressure due to water elevation upstream of the bridge can be minimized.

The choice of the box culvert type runoff bridge has the advantages that in addition to having resistance to hydrostatic pressure because of its mass, the area under pressure from runoff water is relatively small or thin. However, the construction is relatively expensive and requires special attention to the placement area (the riverbed must be hard) so that the chance of being carried away by flood can be minimized. For this reason, each box culvert unit must be joined into a single unit, so that the accumulated mass of the precast concrete becomes the basis for the resistance to the flow of runoff water that passes (KPUPR, 2021a).

Accordingly, it could be inferred that the main strategy to improve the road and bridge management strategy is by increasing the level of accessibility, by prioritizing road and bridge preservation suited to type and scale of damage, including the use of an appropriate type of construction, construction method, and materials. Table 6 shows not only how much the predicted level of accessibility increases due to a decrease in travel time, but also how much the economy expands based on the predicted increase in trips.

It can be seen that if the preservation was undertaken based on the level of damage and the availability of budget to cover preservation costs, then the reduced accessibility level is much influenced by the total length of damaged road sections. In scheme 1, a reduced accessibility index in Waingapu city and main connecting road network are around 3.88% (16.12%-15.63%) and 10.39% (34.34%-31.96%), respectively. The accessibility level may increase significantly if all heavy and medium road damages are repaired concurrently, so that it may be reduced by 1.95% (16.12-4-10.1/103.13) and 3.05% (34.34-23.175-7.885/107/43). In this case, since the total length of all types of roadways in East Sumba Regency is around 1,227.45 km, the improvement of roads within the medium and heavy damage categories may increase not only the level of accessibility but also number of trips. However, since no data towards number of economic trips is available, it is assumed that the economic expansion due to increase in accessibility level is linear with it. Additionally, the predicted number of daily commuter trips along the main connecting roads is simply stated as twice greater than before being repaired. This is a limitation of the current study. Therefore, it is suggested that further study could focus on more accurate evaluation of effects of accessibility improvements on socio-economic trips.

4. Conclusions

The locations of centers of leading economic activity need to be connected, but damage to road segments occurs sporadically. Thus, the main strategy is based on efforts to increase accessibility and mobility simultaneously on the main roads connecting such centers to each other. The use of a digital database system which would allow public to participate by submitting in real time information on type and location of damage to road segments or bridge elements may help improve road and bridge management system, especially in reducing the cost of collecting such data, which thus far is usually undertaken by a technical consultant.

Additionally, there are still many river crossings without bridges, due to financial constraints. Since the crossings are difficult to pass during the rainy season, despite the relatively shallow water level and relatively flat riverbed, the proposed solution is to construct a runoff bridge, which is relatively inexpensive but effective. The results of this study are anticipated to be helpful in conditions that are comparable to those in East Sumba.

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Table 6. Predicted level of accessibility and economic expansion

Observed road segment	Road length (km)	Poor road segments (km)				Current access. index (%)	Predicted accessibility index (%)			Predicted number of daily commuter trips		
		Light damage	Medium damage	Heavy damage	Total		Scheme 1	Scheme 2	Scheme 3	Scheme 1	Scheme 2	Scheme 3
(1)	(2)	(3)	(4)	(5)	(6) = (3+4+5)	(7) = (6)/(2)x 100	(8) = (6-5)/(2)x 100	(9) = (6-4)/(2)x 100	(10) = (6-3)/(2)x 100	(11)	(12)	(13)
Waingapu district	103.130	1.957	10.1	4	16.12	15.63	11.75	5.84	1.90	NA	NA	NA
Main roads that connect the main economic activity centers	107.43	3.28	7.885	23.175	34.34	31.96	21.57	7.34	3.05	1	2	2

Scheme 1 = Preservation of heavy damage only, scheme 2 = preservation of medium damage only, scheme 3 = preservation of light damage only
Source: Result of analysis, 2023

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