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Enhancing Road Safety in Mountainous Regions: Risk Assessment and Improvement Strategies

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Abstract

The goal of zero road fatalities is a global issue. The UN Decade of Action for Road Safety 2011–2020 has successfully reduced road traffic fatalities through global awareness campaigns, aiming to halve road traffic fatalities by 2030. Road safety strategies also support the Sustainable Development Goals (SDGs). Factors influencing crashes include road design, traffic behavior, vehicles, and the environment. On the other hand, the number of crashes in mountainous tourist areas is still very high. This study examines road safety conditions in mountainous regions, focusing on three roads leading to Mount Bromo, East Java, Indonesia. Using the International Road Assessment Program (iRAP), the study evaluates road infrastructure based on crash risk, providing targeted improvement strategies for each road section. The study reveals a high crash frequency on the Lumbang, Sukapura, and Bromo roads, highlighting significant deficiencies in road geometry, signage, and pedestrian facilities. Applying a risk analysis methodology, the study identifies critical areas requiring immediate intervention and categorizes risk levels from "No Hazard" to "Very Hazardous." The findings highlight the need for increased lane widths, improved shoulder areas, better signage, and pedestrian safety measures. Tailored recommendations for each road segment from the road section include road widening, land access controls, traffic signage, and improved street lighting. The results provide valuable insights for policymakers in developing countries, contributing to improved road safety in mountainous and rural areas. The study concludes by urging a proactive approach to road safety, integrating engineering solutions with sustainable practices to reduce crashes and fatalities.

Keywords

road safety, road safety improvements, rural road safety, traffic accidents, mountainous roads terrain, roadworthiness test

1 Introduction

Zero fatality due to traffic accidents is not a new topic of global issue. The Decade of Action for Road Safety 2011–2020 was established by the United Nations (UN) in March 2010. This initiative has succeeded in stabilizing and reducing the number of fatal road traffic accidents worldwide by actively campaigning for road safety and road safety awareness at the national, regional, and global levels (Ishak and Rahim, 2020; UNTAD, 2017). United Nations Resolution A/RES/74/299 on Enhancing Global Road Safety marked the proclamation of the 2nd Decade of Action for Road Safety Program 2021–2030. By 2030, the United Nations targets at least a 50% reduction in road traffic accidents causing fatal and serious injuries (Murozi et al., 2022). Moreover, road safety strategies support the Sustainable Development Goals (SDGs) targets.

Many factors affecting road accidents have been identified, including road and traffic characteristics, drivers' and road users' behavior, vehicles, and the environment. (Huvarinen et al., 2017; Kriswardhana et al., 2019; Wang et al., 2012). According to engineering principles, roads are expected to influence road safety significantly. The influence of road infrastructure on road safety is multifaceted, with road geometry. (Zahra et al., 2024; Kassa et al., 2024; Palupi et al., 2024), pavement quality

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(Al-Masaeid, 2025; Ivanović et al., 2024; Zahidy et al., 2024), and traffic control measures play critical roles in accident occurrence and severity (Khattak et al., 2024; Lee et al., 2025; Palupi et al., 2024; Zahidy et al., 2024). Research indicates these factors significantly impact traffic safety, necessitating integrated interventions to mitigate risks. The following sections explore the specific contributions of road geometry, pavement quality, and traffic control measures to road safety.

Enhancements in geometric design and infrastructure can contribute to safer conditions. Safety is a key objective in highway design (Lamm et al., 1999), such as aligning the intended operating speed with the developmental context of a roadway. A study on sections of the arterials in Washington State found the positive relationships between annual accident frequency and road characteristics, such as the width of the lanes and the tangent length before a horizontal curve (Milton and Mannering, 1998). Similar results were found in another study in the US, where increased lane widths and the number of lanes contributed to increased fatalities (Noland and Oh, 2004). Another study in England and Wales argues that areas with straighter roads have more road accidents (Haynes et al., 2007). A recent survey in Colombia resonates with previous findings by confirming that increasing road width increases the risk of road accidents (Ramírez and Valencia, 2021). Road geometric design, including curve radius, superelevation, and grade, significantly affects accident rates. Clear zones and road grade have been shown to influence 50.04% and 57.00% of accident frequency, respectively, indicating their substantial impact (Palupi et al., 2024). Unsafe roadside designs can exacerbate accident severity, as seen in the European route E68 case study, where improper roadside elements contributed to high accident rates (Kassa et al., 2024). The relationship between road geometry and pavement conditions highlights the need for efficient road management to enhance safety. The Pavement Condition Index (PCI) is positively linked to road and shoulder width but negatively associated with transverse and longitudinal road slopes (Zahra et al., 2024). Although previous studies confirm a relationship between traffic accidents and road characteristics, most studies are conducted on highways with flat terrain. Moreover, most of the previously mentioned studies were undertaken in developed countries.

Road infrastructure with adequate pavement quality can contribute to realizing safe roads. The state and quality of the roadway directly influence traffic safety. Road surface condition affects the adhesion coefficient, which is determined by the level of grip efficiency. (Ivanović et al., 2024). Pavement conditions, measured by the Pavement Condition Index (PCI), have a parabolic relationship with accident frequency and rates. Urban sections with PCI below 50 or above 85 have higher accident rates. (Al-Masaeid, 2025). Pavement friction and roughness influence accident severity, particularly during adverse weather conditions. Poor pavement conditions can lead to more severe multi-vehicle crashes on low-speed roads. (Zahidy et al., 2024).

Traffic control measures are another critical factor in improving road safety. Traffic patterns, such as peak hours and risky driving behaviors, also contribute to accident risks, highlighting the need for effective traffic regulation enforcement. (Palupi et al., 2024). Traffic volume and cross-section design strongly correlate with crash frequency and infrastructure design factors. Key predictors of crash frequency include lane width, the number of lanes, road separation, on-street parking, and the posted speed limit. (Khattak et al., 2024). Vehicle length and traffic volume are significant factors in accident likelihood. As the number of heavy vehicles increases, the probability of accidents also rises. However, wider lanes and shoulders reduce the possibility of accidents as their dimensions increase. (Lee et al., 2025). Road service quality, including maintenance and drainage, significantly correlates with road traffic accidents (RTAs). Poor road surface conditions and inadequate drainage are predictors of increased RTAs (Zahidy et al., 2024). While the primary focus is on road infrastructure, it is essential to consider other factors such as driver behavior, weather conditions, and demographic influences, which also play significant roles in road safety. Combined with infrastructure improvements, these elements can provide a comprehensive approach to reducing accidents and enhancing road safety.

The International Road Assessment Programme (iRAP) is an example of a systematic road assessment program aimed at creating safer roads and reducing accident potential. (Joshua and Setyarini, 2021). It uses a star rating system to evaluate road infrastructure elements. (iRAP, 2022). While such international protocols exist, their application in mountainous contexts of developing countries remains limited. Studies applying iRAP have predominantly focused on urban or flat terrains, such as Jakarta and Balikpapan, Indonesia. (Joshua and Setyarini, 2021; Ryandi and Setyarini, 2021). In contrast, this study employs a risk-based assessment methodology derived from Indonesian road safety audit standards (as outlined in Section 2) to evaluate the specific challenges of mountainous roads, filling a critical gap in both literature and practice.

Road safety studies on mountainous roads are minimal and tend to analyze blackspots. Road safety research on mountainous roads must be developed to improve safety in reviewing safer roads. While road safety evaluation and improvement studies have been conducted, much remains to be explored, especially concerning the mountainous roads in developing countries. Specifically, we emphasize that while international studies have addressed mountainous road safety using approaches such as Bayesian hierarchical models (Ahmed et al., 2011) and spatial alignment analysis (Wang et al., 2022), a limited body of research focuses on mountainous rural roads in developing countries using a risk-based assessment. Thus, current research aims to evaluate road safety levels in mountainous areas and propose the relevant improvements using a risk analysis approach. This study has important implications for policymakers regarding improving road safety in mountainous regions of developing countries, contributing to the road safety literature as well. Our study, therefore, contributes by applying this methodology to the Mount Bromo tourist road network in Indonesia, highlighting context-specific deficiencies and improvement strategies.

The remainder of the paper is structured as follows. Section 2 elaborates on the review of existing literature on road safety evaluation in developing countries, especially in Indonesia. The data collection methods and analysis are presented in Section 3. Section 4 reports the results, followed by the discussion in Section 5. Finally, Section 6 summarizes the findings.

2 Literature review

Road infrastructure plays a vital role in the development of the tourism industry. Providing easy access to tourist destinations by improving road and transport infrastructure could increase business activities and promote new tourist attractions. Previous studies confirm a positive relationship between tourist activities and road activities. (Oktopianto and Anggara, 2022). In a nutshell, the flow of tourism partly depends on the road and transportation infrastructure. However, merely providing road infrastructure to support tourism is not enough. Besides the ease of accessing the destinations, the safety of the roads must be guaranteed.

Traffic accidents result from unplanned and uncontrollable actions, occurring due to actions and reactions to an object that can cause injury. (Fatonah et al., 2018). Traffic accidents are events that cannot be predicted to occur. Accidents can result in pain, trauma, injury, or fatalities.

The type of accident is classified into several collisions: front-front, front-rear, corner collision, side collision, out-of-control, hit-and-run, mass collision, pedestrian collision, parking collision, and single collision. At PT Jasa Marga Groups, a prominent toll road management company in Indonesia, the types of collisions that underlie traffic accidents are:

1. front-to-front collision;
2. front-side collision;
3. front-rear collision;
4. side-side collision;
5. hitting a pedestrian;
6. self-collision;
7. pile-up collision;
8. hitting a fixed object.

A safer road is a road that provides a sense of security, comfort, stability, and safety because it takes into account the interaction between road users, vehicles, road geometry, traffic operations, and the surrounding environment, and minimizes the risk and severity of traffic accidents. (Directorate General of Highways, 2012; Mulyono et al., 2009; Pandey, 2013). A safer road is a concept where all traffic management is adjusted to the capabilities of road users to prevent accidents involving road infrastructure. (Directorate General of Highways, 2024). There are four essential criteria for realizing a safe road:

1. Forgiving road is one on which a dangerous situation and conditions may still occur due to human system failure. However, the road environment is expected to provide an excellent opportunity for road users to avoid accidents that result in high fatality rates.
2. Self-explanatory road signs can inform road users about non-standard conditions so that road users can take anticipatory steps.
3. Self-regulating roads mean that roads are built to follow the geometric rules or regulations that the Government has set in its regulations.
4. Self-enforcing road, a road design that can create compliance for road users by maximizing the use of signs, markings, and signals so that road users remain on track.

Road safety audits are conducted by ranking roads according to safety level to determine the priority of road safety inspections under limited funding conditions. Statistical data processing methods for road analysis can be carried out according to the safety level. (Huvarinen et al., 2017). Analysis of road safety levels is measured using the road safety function test method based on the Procedures and Requirements for Road Function

Worthiness. (Directorate General of Highways, 2014). The aspects tested include road geometry, road pavement, road supplementary buildings, utilization of road sections, implementation of traffic management and engineering, and road equipment facilities. The expected benefits are to prevent or reduce the possibility of accidents on the road section.

The road safety audit method (Directorate General of Highways, 2024) is used in the analysis approach to determine the risk value from the results of roadworthiness tests, with the following approach:

1. Priority handling of hazards is based on assessing each critical point that can cause a safety hazard.
2. Critical safety hazards (e.g., those posing an immediate and severe threat) are recorded and reported separately for immediate action and do not undergo the standard risk scoring process.
3. Accident risk (R) is the result of multiplying the probability value (P) of the hazard that causes accidents and the severity impact value (D). The probability (P) and severity (D) are rated on a numerical scale (e.g., 1 to 5 and 1 to 100, respectively), where a higher number indicates greater probability or severity.
4. The Probability value (P) is estimated based on deviations of dimensions and layout of road infrastructure parts from technical standards (see Table 1).
5. The Severity value (D) is estimated based on the potential consequences of an accident at the identified hazard, using the classification in Table 2.

This study clearly explains and references the analysis of the accident, ability, and severity impact categories. Specifically, Tables 1–3 (Accident Cause Probability, Severity Impact, and Risk Value Categories) are directly attributed to the road safety audit method. (Directorate General of Highways, 2024) and (Mulyono, 2021). This analysis results from multiplying the value of the probability of causing an accident by the value of the severity of the impact. (Mulyono, 2021). The formula for calculating the accident risk value can be seen in Eq. (1).

$$R = P \times D \tag{1}$$

Where:

- R = Accident risk;
- P = Accident cause probability;
- D = Severity impact.

Table 1 Accident cause probability

Measurement results of dimensions and layout of road infrastructure parts	Qualitative value	Quantitative value
The measured difference in the field is less than 10% of the technical standard	Never had an accident	1
The measured difference in the field is between 10% to 40% of the technical standard	Accidents occur up to 5 times per year	2
The measured difference in the field is between 40% to 70% of the technical standard	Accidents occur up to 5–10 times per year	3
The measured difference in the field is between 70% to 100% of the technical standard	Accidents occurred up to 10–15 times per year	4
The measured difference in the field is greater than 100% of the technical standard	Accidents occur more than 15 times per year	5

Source: Directorate General of Highways (2024) and Mulyono (2021)

Table 2 Severity impact

Evacuation results of road accident victims	Qualitative value	Quantitative value
The victims did not experience any injuries except for material losses	Very light	1
The victim experienced minor injuries and material losses	Light	10
The victim experienced serious injuries and had no potential for limb disability, and there was or was not material loss	Currently	40
The victim experienced serious injuries and had the potential to die during the treatment process at the hospital or healing center, and there was or was not material loss	Heavy	70
The victim died at the scene of the accident, and there was or was not material loss	Very heavy	100

Source: Directorate General of Highways (2024) and Mulyono (2021).

Table 3 Risk values and categories and levels of deficiency management

Risk analysis		Level of importance of handling
Risk	Risk category	
<125	Not dangerous (ND)	Routine monitoring with scheduled road safety inspections at points that have the potential for accidents
125–250	Moderately dangerous (MD)	Unscheduled technical handling based on the results of road safety inspections at the location of the incident and its surroundings.
250–375	Dangerous (DD)	Scheduled technical handling within a maximum of 2 months since the road safety audit results are approved.
>375	Very dangerous (VD)	Total technical handling with related stakeholders a maximum of 2 (two) weeks since the road safety audit results are approved

Source: Directorate General of Highways (2024)

The risk assessment method used in this study adopts the 5 × 5 risk matrix officially regulated in the Regulation concerning Technical Guidelines for Road Safety Audits. This matrix combines five levels of probability (P) and five levels of severity (D). The probability level (P) is determined based on an integrated assessment of both the degree of deviation of the road element from applicable technical standards and the historical accident frequency at the location. These two factors complement each other: a high deviation supported by a poor accident record will result in the highest probability rating ($P = 5$). In the absence of accident data, the assessment relies on deviation analysis. Meanwhile, the severity level (D) refers to the classification of accident impacts stipulated in the same regulation, ranging from material losses to fatalities. Thus, this framework is consistent with Indonesian road safety audit practices and explicitly draws on applicable regulations.

The value of the accident-cause opportunity can be estimated based on the number of accidents, deviations from technical standards, road user behavior, and traffic complexity. At the same time, the value of the severity impact can be estimated based on the history of similar accidents and deficiencies.

Each traffic safety deficiency can be classified based on the urgency of the handling response for traffic safety, which can be done by considering the risk value (R). The urgency of traffic safety deficiency can be adjusted in Table 3.

In calculating the risk value, it is necessary to obtain deficiency results based on field measurement results with existing technical standards. To calculate the deficiency value, we can use Eq. (2) as follows.

$$\text{Deficiency} = \left(\frac{\text{Technical Std} - \text{Measurement}}{\text{Technical Std}} \right) \times 100\% \quad (2)$$

After getting the deficiency value for a component, one can find the opportunity value of a subcomponent based on Table 1. Then, one can input the impact value on each subcomponent by analyzing the fatality rate and accident type based on existing accident data. The quantitative value of this impact value refers to Table 2 and adjusts it to the results of the accident fatality rate analysis. Then, after calculating the opportunity and impact values, one can determine the risk value based on Table 3. After getting the risk value, a subcomponent can be identified as having a risk category ranging from Not dangerous (ND), Quite dangerous (QD), Dangerous (DD), or Very dangerous (VD).

3 Methodology

3.1 Data collection and study location

Road access to the Mount Bromo tourism area from Probolinggo is the study location. Mount Bromo in East Java is one of the national priority tourist attractions. (Yoga, 2018). Safe and comfortable road infrastructure is needed to support this tourist area (Oktopianto and Anggara, 2022). Mount Bromo can be accessed via Probolinggo. Fatal traffic accidents in 2023 were recorded twice, resulting in 1 death and nine serious injuries. In 2022, there was one fatal accident resulting in two fatalities and four serious injuries. Meanwhile, based on the results of a study (Sulistyono et al., 2024) five blackspots were identified on the road access to Mount Bromo tourism area. Thus, based on the previous arguments, road sections to Mount Bromo are relevant to be evaluated, given the aim of the study. Three sections were identified based on the field observation, namely: (a) Section 1 (Lumbang Road section), namely from Tongas intersection to Tugu Wisata Bromo intersection; (b) Section 2 (Sukapura road section), namely from Tugu Adipura intersection to Tugu Wisata Bromo intersection; and (c) Section 3 (Bromo road section), namely from Tugu Wisata Bromo intersection to Ngadisari. The illustration of the road sections is provided in Fig. 1.

The official iRAP star rating framework was applied to evaluate road safety performance. Each road segment was assessed on a scale from 1-star (very high risk) to 5-star (very safe), based on the presence and quality of infrastructure features. Data were encoded and analyzed using ViDA (the iRAP online platform), which allows standardized input and automated calculation of star ratings and risk scores. Field observations collected every 100 meters (covering road geometry, lane and shoulder widths, signage, pedestrian facilities, lighting, etc.) were digitized into ViDA. While the

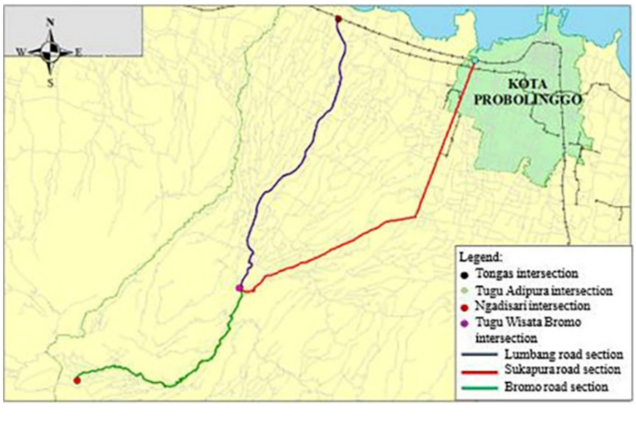

Fig. 1 Road sections

iRAP framework provided the infrastructure-based star ratings, we complemented this with the risk value calculation, Eq. (1), derived from Indonesian road safety audit standards. This dual approach strengthens the robustness of the methodology by combining an internationally recognized framework with a locally regulated risk assessment method.

Primary data were obtained from direct observations at the research location. These are cross-sectional data of roads, daily traffic, road infrastructure, and speed. Data collection was carried out along the road sections every 100 m. Secondary data were obtained from related institutions through location maps, road status, road classification, and traffic accident data from 2018 to 2022. The crash data utilized in this study were obtained from the road crash information system maintained by the Indonesian National Police's Traffic Corps from the Indonesian Road Safety Management System (IRSMS).

3.2 Data analysis

Primary data were obtained from road safety inspections using a roadworthiness test approach on the research object road sections. Road inspections were done by directly observing and measuring every 100 m of the road segment. The road technicalities that must be considered during road inspections by the rules in roadworthiness tests include road geometry, road pavement, road equipment, utilization of road sections, traffic management, and engineering

Roadworthiness test is an analysis that compares the results of observations with road technical requirements and assigns categories to each road subcomponent. The level of difference from the comparison creates a category of roadworthiness levels on each road segment by considering each road subcomponent; the categories in question are Functional Worthiness (FW), Conditional Functional Worthiness (CFW), Functional Worthiness with Reduced Technical Requirements (LFW), and Not Functional Worthiness (NFW).

4 Results

4.1 The characteristics of road traffic accidents

The accident characteristics on the tourist access roads to Mount Bromo vary based on the specific conditions of each road that contribute to accidents. The number of traffic accidents on the Lumbang Road section between 2018 and 2022 was 69 incidents. The Lumbang road section experienced a total of 11 fatalities and 58 injuries, where the highest fatality and injury rates occurred in 2021, with five incidents resulting in fatalities and nine incidents causing five fatalities and 16 injuries. Front-to-front or front-to-side collisions are the dominant type of accidents, most of which occur when vehicles turn. The transitions of terrain characteristics from flat to hilly are one of the potential areas where this type of collision is prevalent. Traffic accident data on the Lumbang Road section can be seen in Fig. 2.

The number of traffic accidents on the Sukapura road section between 2018 and 2022 was 229 incidents. As presented in Fig. 3, the Sukapura road section recorded a total of 48 fatalities and 181 slight injuries. The highest rates of deaths and minor injuries occurred in 2019, with 10 fatal incidents and 54 incidents resulting in minor injuries. The dominant crash type was a collision during a turn (to the left or right side of the road), where 24 crashes occurred. This type of accident is the same as in the Lumbang Road section, where the road characteristics of the Sukapura road section are similar to those of the Lumbang Road section. However, they are different in class and road management authority.

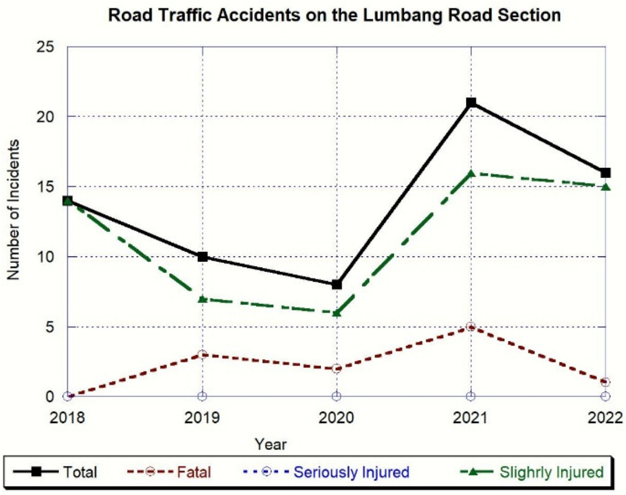

Fig. 2 Road traffic accidents on the Lumbang road section

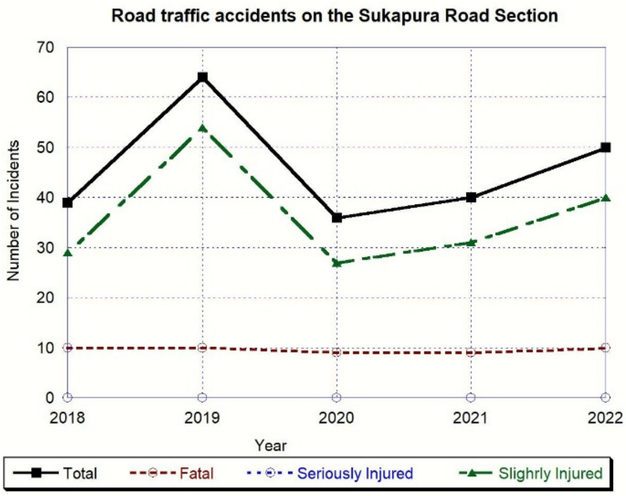

Fig. 3 Road traffic accidents on the Sukapura road section

Front-to-front or front-to-side collisions are the dominant type of accident that occur, most of which occur when vehicles turn. The transitions of terrain characteristics from flat to hilly are one of the potential areas where this type of collision is prevalent.

As outlined in Fig. 4, the Bromo road section recorded nine fatal and 29 slight injuries from accidents. During the period from 2018 to 2022, the highest fatality and minor injury rates occurred in 2019, with three fatal incidents and eight incidents involving slight injuries. There were 15 front-to-front collisions. This type of collision stands out compared to other types of collisions. This condition is made possible by the terrain conditions on the Bromo road section, a mountainous terrain area.

The types of road accidents in mountainous areas have different characteristics from those in urban areas. The details of accident data based on the cause of the accident can be seen in Table 4. The table shows the most prevalent causes of accidents in each road section. The survey results show three causes of the same incident in 3 road sections: vehicle out of control, front-front collision, and front-rear collision, while the rest vary significantly in each road section. The most significant accident rate is observed in the Sukapura road section, followed by the Lumbang and Bromo road sections.

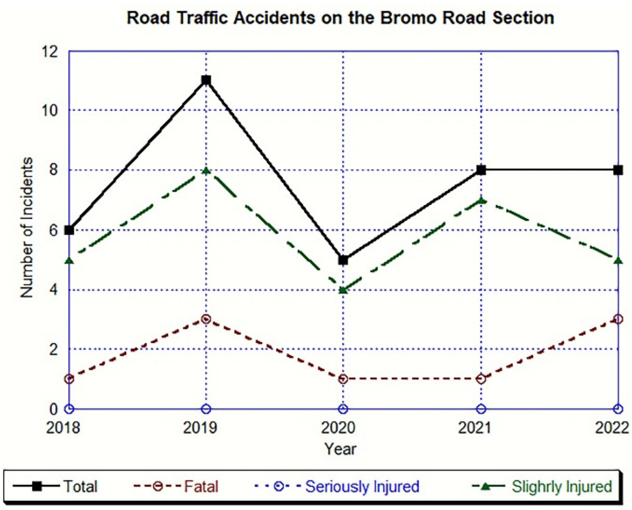

Fig. 4 Road traffic accidents on the Bromo road section

Table 4 Dominant accident types in each road section

Type	Lumbung	Sukapura	Bromo
Vehicle out of control	8	20	8
Front-to-front collision	4	18	15
Front-to-rear collision	4	13	0
A collision while turning to the left or right side of the road	0	24	0
Collision while overtaking	0	21	0
Vehicle turning collision	12	0	0
Vehicle collision while overtaking	7	0	0
Collision with a parked vehicle	0	0	2
Collision with a vehicle coming from the opposite direction	0	0	2

4.2 Accident risk

The calculation of risk value analysis is carried out to determine the deviation of road sub-components between technical requirements and existing conditions on the Sukapura section; the calculation process refers to the literature on risk analysis and Tables 1–3 on accident probability value, severity impact value, and accident risk value. The results of the risk analysis calculation are in the form of a risk value categorization consisting of 4 risk levels, namely Not dangerous (ND), Moderately dangerous (MD), Dangerous (DD), and Very dangerous (VD). For example, the following are the risk analysis calculation tables on the 5th Sukapura segment (KM SBY 94 + 600 − 94 + 700), as seen in Table 5. The same method is carried out on all segments to obtain the risk value of each segment. The risk analysis results will be used as material to determine the risk category on all road segments in the study area.

The risk category determined by using risk analysis of each segment based on components can be seen in Table 6 for the Lumbang Road section, the Sukapura Road section in Table 7, and Table 8 is for the Bromo Road section. These tables show that the Sukapura road section is the most dangerous segment because it has a relatively higher risk than the other two sections, followed by the Lumbang and the Bromo road sections. From these tables, it can be seen that several road components in the Sukapura road section have the highest risk, which is indicated by the most dangerous sub-components marked in red (32 sub-components), dangerous in orange (26 sub-components), quite dangerous as many as 45 sub-components, and the rest are not dangerous. This is based on the number of accidents in Table 4, where the Sukapura road section has the most accidents compared to other segments.

5. Discussion and recommendation

5.1 Discussion

The road safety improvement plan focuses on road subcomponents categorized as high-risk in causing accidents, so it is necessary to improve these subcomponents according to applicable technical standards. The improvement plan for improving road safety in the Lumbang Road section can be

Table 5 Accident risk analysis of road sections sukapura on 5th road segment (KM SBY 94 + 600 – 94 + 700) (for analysis example)

No	Sub-component	Unit	Technical standard	Measurement result	Standard deficiency (%)	Probability	Impact	Risk	Risk category
Geometric									
1	Traffic lane width	m	7	5,7	18,57	2	10	20	ND
2	Traffic width uniformity	%	100	100	0	1	1	1	ND
3	Shoulder width	m	1	0,2	80	4	1	4	ND
4	Shoulder condition	%	100	80	20	2	10	20	ND
5	Side ditch width	m	1	5,7	470	5	1	5	ND
6	Level intersection	point	1	2	100	4	10	40	ND
7	Plot access	point	1	5	400	5	10	50	ND
8	Longitudinal slope	%	10	5.8	42	3	1	3	ND
Pavement									
1	Pavement condition	%	100	100	0	1	1	1	ND
Road utility									
1	Roadside channel	%	100	100	0	1	1	1	ND
Utilization of road cections									
1	Road boundary dimensions	m	13	20,93	60,92	3	1	3	ND
2	Road boundary	%	100	100	0	1	1	1	ND
3	Building line dimensions	m	15	20,93	39,47	3	2	6	ND
4	Building line	%	100	100	0	1	1	1	ND
5	Control line	%	100	40	60	3	1	3	ND
Traffic Management and Engineering									
1	Marking needs	%	100	100	0	1	1	1	ND
2	Sign needs	unit	2	1	50	3	100	300	D
3	Sign placement accuracy	%	100	100	0	1	1	1	ND
4	Sidewalk needs	%	100	40	60	3	10	30	ND
5	Sidewalk utilization	%	100	90	10	2	1	2	ND
6	APILL needs	%	100	100	0	1	1	1	ND
7	Crossing area needs	%	100	100	0	1	1	1	ND
Walkway utility									
1	Marking condition	%	100	100	0	1	1	1	ND
2	Sign condition	%	100	100	0	1	1	1	ND
3	Sidewalk width	m	2	1	50	3	10	30	ND
4	Bus/public transportation stops	%	100	100	0	1	1	1	ND
5	Street lighting	unit	2	1	50	3	1	3	ND
6	Hectometer markers	unit	1	1	0	1	1	1	ND
7	Building line markers	unit	4	1	75	4	1	4	ND

seen in Table 9, the Sukapura Road section in Table 10, and the Bromo Road section in Table 11.

5.1.1 Identification of high-risk subcomponents

The road safety improvement plan begins by categorizing subcomponents of the road that are considered high-risk. These subcomponents are identified based on their potential to contribute to accidents through poor road conditions, insufficient signage, inadequate pedestrian facilities, or other factors. By categorizing these elements, the plan prioritizes areas that require immediate attention, ensuring that limited resources are directed where they can have the most significant safety benefits.

This approach ensures that efforts are concentrated on areas that are most likely to cause accidents, thereby maximizing the potential impact of the improvements on overall road safety. The following further discusses it in detail.

Table 6 Risk category based on road components on the Lumbang cection

Segment	Sub-component																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	DD	ND	ND	ND	ND
2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	VD	ND	ND	ND	ND	ND	ND	ND
3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
15	DD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	VD	ND	ND	ND	ND
21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
26	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
30	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
32	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
39	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
58	ND	MD	ND	ND	ND	ND	ND	ND	ND	VD	ND	ND	ND	ND	ND	ND	ND	ND	ND
67	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
75	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
92	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
117	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
119	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
132	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
134	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
137	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
150	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
153	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
154	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
155	MD	ND	ND	VD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
162	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	VD	ND	ND	ND	ND	ND	ND	ND
169	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
185	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

(1) width of traffic lane; (2) road shoulder; (3) side gutter; (4) land access; (5) land access; (6) culvert; (7) side channel; (8) house; (9) public transportation; (10) roadside; (11) edge marking; (12) guide signs; (13) warning signs; (14) crossing; (15) condition of markings; (16) street lights; (17) guideposts; (18) kilometer markers; (19) public transportation markers

red = very dangerous (VD), orange/light red = dangerous (D), yellow = moderately dangerous (MD), and no shading = not dangerous (ND)

This categorization process is crucial because it allows for a more targeted approach to road safety. For example, if certain road sections are known to have high accident rates due to narrow lanes or insufficient lighting, improvements can be specifically designed to address these issues. Risk factors sometimes include geographical features such as sharp turns, steep gradients, or areas prone to heavy pedestrian traffic.

5.1.2 Technical standards for improvements

The survey shows that these high-risk subcomponents must be improved by "applicable technical standards". This refers to the established guidelines, codes, and best practices in road safety engineering that ensure effective and sustainable improvements. These standards are typically based on national or international safety regulations and are backed by research and experience from traffic safety experts.

The reference to technical standards is essential because it ensures that the improvements are not just arbitrary but are based on proven engineering principles. For example, widening lanes to meet certain specifications or adding road signage that adheres to internationally recognized visibility standards will have a measurable impact on reducing accidents. By following these standards, safety measures will also align with the best global practices, which helps create a safer environment for drivers and pedestrians.

5.1.3 Segment-specific improvements

The improvement plan for the Lumbang, Sukapura, and Bromo road sections highlights the need for tailored solutions in each specific section. Each road segment presents unique challenges that require individualized attention, so the improvements are detailed in separate tables for each segment.

Table 7 Risk category based on road components on the Sukapura section

Segment	Sub-component																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
4	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	VD	DD	ND	ND	ND	DD	ND	ND	ND	ND
16	ND	ND	ND	ND	VD	ND	ND	ND	ND	ND	ND	DD	ND	ND	ND	ND	ND	DD	ND	ND	ND
19	ND	ND	ND	ND	VD	ND	ND	ND	ND	ND	ND	VD	ND	ND	MD	ND	ND	VD	ND	ND	ND
47	ND	MD	ND	ND	ND	ND	MD	ND	ND	ND	ND	DD	ND	ND	ND	ND	ND	VD	ND	ND	ND
50	ND	ND	DD	ND	ND	ND	ND	MD	ND	MD	VD	DD	VD	MD	MD	ND	ND	ND	ND	ND	ND
52	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	DD	ND	ND	DD	ND	ND	DD	ND	ND	ND
53	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
70	MD	MD	MD	ND	DD	ND	ND	ND	ND	ND	ND	DD	ND	MD	VD	ND	ND	DD	ND	ND	ND
74	MD	DD	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	VD	ND	ND	VD	ND	ND	ND
79	MD	MD	MD	ND	ND	ND	MD	ND	ND	ND	ND	ND	ND	ND	VD	ND	ND	VD	MD	ND	ND
81	MD	MD	ND	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	VD	ND	VD	MD	ND	ND
82	MD	ND	DD	ND	VD	ND	ND	ND	ND	ND	ND	ND	ND	ND	DD	ND	ND	VD	MD	ND	ND
90	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	DD	ND	ND	VD	MD	ND	ND
92	MD	ND	DD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	VD	MD	ND	ND
94	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	DD	DD	ND	VD	MD	ND	ND
101	MD	ND	DD	ND	ND	ND	MD	ND	MD	ND	ND	ND	ND	ND	DD	ND	ND	DD	ND	ND	ND
125	ND	DD	ND	ND	ND	ND	MD	ND	MD	MD	ND	VD	ND	ND	ND	ND	ND	VD	MD	ND	ND
127	ND	DD	ND	ND	ND	DD	MD	ND	ND	ND	ND	DD	ND	ND	ND	ND	ND	VD	ND	ND	ND
141	ND	ND	ND	ND	ND	VD	ND	ND	MD	ND	ND	VD	ND	ND	VD	ND	ND	VD	ND	ND	ND
163	MD	ND	VD	ND	ND	ND	MD	ND	MD	ND	ND	ND	ND	ND	VD	ND	ND	VD	ND	ND	ND
168	MD	ND	DD	ND	ND	ND	MD	ND	MD	ND	ND	ND	ND	ND	VD	ND	ND	VD	ND	ND	ND

(1) width of traffic lane; (2) road shoulder; (3) side gutter; (4) land access; (5) land access; (6) culvert; (7) side channel; (8) house; (9) public transportation; (10) roadside; (11) edge marking; (12) guide signs; (13) warning signs; (14) crossing; (15) condition of markings; (16) street lights; (17) guideposts; (18) kilometer markers; (19) public transportation markers

red = very dangerous (VD), orange/light red = dangerous (D), yellow = moderately dangerous (MD), and no shading = not dangerous (ND)

Lumbang road section (Table 9): The safety improvements proposed for Lumbang focus on widening lanes and shoulders, controlling land access, and enhancing signage. The recommended technical measures, such as installing bend warning signs and improving lane markings, directly address the identified high-risk elements in this segment.

Sukapura road section (Table 10): The improvements to the Sukapura road section emphasize pedestrian safety by installing sidewalks in school zones and crossing facilities in public areas. Additionally, road markings and signage improvements are recommended, which are necessary to address both pedestrian and vehicle safety concerns.

Bromo road section (Table 11): Bromo focuses on traffic flow and road infrastructure repair, including widening lanes and improving guardrails. Specific challenges like steep gradients and sharp curves are addressed by installing appropriate warning signs and ensuring drivers are adequately informed about potential hazards.

This segment-based approach allows for a more context-sensitive application of road safety improvements. By assessing each road segment's unique features and risks, authorities can ensure that the changes made are not generic but customized to tackle the specific safety concerns in each area effectively. For example, the need for particular signage at kilometer marks in each segment reflects a deep understanding of local road conditions.

5.1.4 Overall road safety strategy

The overall road safety strategy aims to reduce accidents by making targeted improvements to high-risk subcomponents based on a thorough understanding of each road section's characteristics. This strategy reflects modern safety management practices, emphasizing data-driven decision-making and prioritizing interventions with the highest potential to reduce accidents and fatalities.

The approach also suggests a more proactive and preventive stance on road safety. Instead of waiting for accidents to occur before taking action, improvements are being made based on anticipated risks. This forward-thinking strategy helps prevent accidents before they happen, which is far more effective and efficient than reactive measures. This approach aligns with the exploration for developing road safety index

Table 8 Risk category based on road components on the Bromo section

Segment	Sub-component																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	ND	ND	ND	ND	ND	ND	MD	ND
6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
11	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	ND	ND	ND	ND	DD	ND	ND	ND	ND	ND
13	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
15	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
17	MD	DD	ND	ND	ND	ND	ND	ND	ND	ND	ND	DD	ND	ND	ND	MD	ND	ND	ND	ND	MD	ND
18	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
22	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
28	MD	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	ND
43	MD	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	MD
44	ND	ND	ND	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
51	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
53	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
56	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	ND	ND	ND	ND	ND	ND	ND
63	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	DD	ND	ND	ND	ND	ND
75	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND
78	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
87	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
103	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND
107	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
110	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
141	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	MD	ND	ND	ND	ND	ND	ND	ND	ND	ND
154	MD	ND	ND	ND	ND	ND	ND	ND	MD	ND	ND	ND	ND	DD	ND	ND	ND	ND	ND	ND	ND	ND

(1) width of traffic lane; (2) road shoulder; (3) side gutter; (4) land access; (5) land access; (6) culvert; (7) side channel; (8) house; (9) public transportation; (10) roadside; (11) edge marking; (12) guide signs; (13) warning signs; (14) crossing; (15) condition of markings; (16) street lights; (17) guideposts; (18) kilometer markers; (19) public transportation markers

red = very dangerous (VD), orange/light red = dangerous (D), yellow = moderately dangerous (MD), and no shading = not dangerous (ND)

results, with the design of roads and general public awareness as the primary safety index. (Fatima et al., 2024; Directorate General of Highways, 2014; Directorate General of Highways, 2024; Mulyono, 2021).

5.2 Recommendation

The study gives some recommendations for road safety improvements across three sections: Lumbang, Sukapura, and Bromo. These sections likely serve as essential routes with significant vehicle and pedestrian traffic. To construct a comprehensive recommendation, we must explore the technical aspects and the broader implications of these recommendations for road safety and transportation planning.

5.2.1 Geometrics and traffic flow

One of the central elements for enhancing road safety in all three road sections is improving the geometrics of the roads, which includes widening traffic lanes and road shoulders. For instance, increasing the lane width to 3.5 meters and widening the shoulder to 1 meter in the Lumbang and Bromo road sections is a key recommendation. These measures improve traffic flow, reduce the likelihood of accidents due to lane restrictions, and provide emergency space for vehicles, which is crucial in case of breakdowns or accidents.

Some may argue that lane and shoulder widening improves traffic flow and safety; it may also increase road capacity, potentially leading to higher traffic volumes and creating new challenges such as congestion or environmental impact (e.g., increased air pollution and noise). A detailed environmental impact assessment should accompany these recommendations to ensure safety improvements do not inadvertently lead to adverse outcomes.

On the other hand, wider lanes and shoulders can mitigate the risk of accidents, especially in areas with sharp curves, high gradients, or heavy traffic, such as in the Bromo road section, where the recommendation to

Table 9 Road safety improvement efforts on Lumbang road section

No	Sub-component	Recommendations to enhance road safety
Geometrics		
1	Traffic lanes	Increase the lane width to 3.5 m on the Lumbang Road section
2	Road shoulder	Increase the width of the road shoulder to 1 m on the Lumbang section
3	Plot access	Carry out land access control
Implementation of traffic management and engineering		
1	Markings	Adding lane edge markings on the Lumbang Road section
2	Signs	Installing crossing signs at KM TGS 0+000 Installing speed reduction warning signs at KM TGS 0+100 – KM TGS 0+200 Installing bend warning signs at KM TGS 15+400 – KM TGS 15+500 Installing uphill and caution warning signs at KM TGS16+100 – KM TGS 16+200
Technical road equipment directly with road users		
1	Markings	Repainting road markings
2	Signs	Replacing damaged signs at KM TGS 1 + 700 – KM TGS 1 + 800, KM TGS 11 + 900 – KM TGS 12 + 000, KM TGS 18 + 700 – KM TGS 18 + 800, and KM TGS 18 + 800 – KM TGS 18 + 900
3	Lighting lamp	Installing street lighting at a distance of 50 m

increase the lane width and install guardrails in specific sections is crucial for handling uphill/downhill roads.

5.2.2 Signage and marking

Signage and road markings are critical for ensuring drivers are adequately informed of the road conditions ahead. The recommendations for adding, replacing, or repainting lane markings and installing cautionary signs (e.g., warning for bends, speed reductions, and uphill slopes) in all three road sections are consistent with established road safety protocols.

While signage is an effective way to inform drivers and enhance safety, there is an ongoing debate about road signs' over-saturation and effectiveness. Over-signaling could lead to driver complacency or confusion, especially when signs are too frequent or redundant.

The importance of signs, especially in critical areas such as sharp bends and intersections, cannot be overstated. In the case of the Sukapura and Bromo road sections, where there is a mix of steep gradients and curves, proper signage ensures that drivers are adequately prepared for road conditions, thus reducing the likelihood of accidents.

Table 10 Road safety improvement efforts on Sukapura road section

No	Sub-component	Recommendations to enhance road safety
Geometrics		
1	Shoulder width	Widening the road shoulder according to the needs and technical standards of at least 1 m on the Sukapura road
2	Plot access	Controlling land access and arranging signs and markings
3	Longitudinal slope	Arranging traffic signs and markings according to the needs of environmental conditions.
Implementation of traffic management and engineering		
1	Marking needs	Fulfilling marking needs according to the needs of a road section, especially in bend areas, intersections, and areas that require crossing facilities along the Sukapura Section.
2	Sign requirements	Fulfilling the need for signs according to environmental conditions in segments 4, 5, 16, 19, 45, 47, 53, 70, 125, 126, 127, and 163.
3	Sidewalk needs	Requires facilities for pedestrians, namely sidewalks in the school area in segment 4 (KM SBY 94 + 500 – 94 + 600) and segment 50 (KM SBY 99 + 100 – 99 + 200)
4	Need for crossing places	There is a need for crossing places in the public facilities area on segment 53 (KM SBY 99 + 400 – 99 + 500)
Road equipment related and not directly related to road users		
1	Marking condition	Repainting faded markings on the Sukapura Highway section
2	Street lighting	Install street lighting at a distance of every 50 m on the Sukapura road.
3	Guideposts	There is a need for guideposts equipped with delineators in bend areas.

5.2.3 Pedestrian safety

In both the Sukapura and Bromo road sections, recommendations to address pedestrian safety stand out, especially in areas with schools or public facilities. The need for sidewalks and crossing places is highlighted as essential to protecting pedestrians. In particular, the Sukapura road section requires sidewalk facilities in school areas (KM SBY 94 + 500 – 94 + 600) and the installation of crossing facilities in public places.

There could be concerns regarding the allocation of space for pedestrians versus vehicles. In regions with heavy vehicle traffic, widening sidewalks may require the reduction of lane capacity, potentially exacerbating traffic congestion. The challenge lies in balancing the needs of pedestrians with the efficiency of vehicular traffic.

Prioritizing pedestrian infrastructure is essential for road safety, particularly in areas with high foot traffic. Encouraging safe pedestrian behavior by providing

Table 11 Road safety improvement efforts on Bromo road section

No	Sub-component	Recommendations to enhance road safety
Geometrics		
1	Traffic lanes	Increase the lane width to 3.5 m on the Bromo road section
2	Road shoulder	Increase the width of the road shoulder to 1 m on the Bromo section
3	Traffic safety equipment	Rail guard repairs are needed on segment 135
4	Plot access	There is a need to control plot access on segment 132, segment 133, and segment 135
5	Straight sections	On uphill/downhill roads with a gradient of > 10%, it is necessary to provide warning signs.
Road utility techniques		
1	Bridge, overpass, underpass	There is a need to repaint the markings on the bridge
Implementation of traffic management and engineering		
1	Signs	There is a need to fulfill the need for signs in segments 11, 28, and 3.
Road equipment related and not directly related to road users		
1	Markings	They need to be repainted as the markings are starting to fade.
2	Sign	There is a need to replace the damaged signpost on Bromo Highway
3	Sidewalk	There is a needs to repair the damaged sidewalk on segment 53
4	Supporting facilities for traffic and road transportation	Streetlights need to be provided every 50 m along the Bromo Highway.
Road equipment related and not directly related to road users		
1	Kilometer markers	There needs to be kilometer markers every 1 km on the Bromo Highway.
2	Hectometer markers	Providing hectometer markers every 100 m on the Bromo Highway section is necessary.

designated sidewalks and crossing points would reduce the risk of pedestrian accidents, which are often severe when pedestrians are forced to walk on the roadway.

5.2.4 Lighting and visibility

The recommendation for street lighting at a distance of 50 meters in all road sections is a crucial safety measure, particularly for driving at night or during low visibility conditions. Proper illumination not only improves driver visibility but also helps reduce the likelihood of accidents, particularly on sections with complex road conditions, such as in the Bromo road section, where gradients and curves create more challenges for nighttime driving.

The issue of lighting may raise concerns about energy consumption and environmental sustainability. The increased use of lighting could lead to higher energy demand, which may not be sustainable in the long run.

The safety benefits of proper lighting cannot be ignored, especially in areas prone to accidents at night. One potential solution is integrating energy-efficient lighting systems, such as LED lights, which reduce energy consumption while enhancing road safety.

5.2.5 Maintenance and monitoring

Routine maintenance and monitoring of road conditions and safety equipment are essential components of these recommendations. Repainting faded markings and replacing damaged signs are critical for maintaining road safety standards. For instance, in the Bromo road section, the need for repainting markings on the bridge and repairing damaged guardrails highlights the importance of maintaining existing infrastructure.

The focus on maintenance, while essential, could divert resources from more forward-looking improvements, such as the construction of new roads or the expansion of public transportation options. Maintenance is a reactive approach compared to proactive infrastructure development.

However, maintaining existing infrastructure cannot be overstated. Neglecting maintenance can lead to deteriorating road conditions, which increases the risk of accidents. A balanced approach with proactive and reactive measures is essential for long-term road safety.

6. Conclusion

The results of this study introduce a well-structured and strategic approach to improving road safety by focusing on high-risk road subcomponents, with improvements made according to recognized technical standards. The plan considers the unique characteristics and risks of the Lumbang, Sukapura, and Bromo road sections by detailing enhancements. This maximizes safety and ensures that interventions are context-specific, well-planned, and compliant with global road safety standards. The proposed road safety improvements for the Lumbang, Sukapura, and Bromo road sections are comprehensive and address several important aspects of road design, signage, pedestrian safety, and maintenance. However, each recommendation must be evaluated holistically, considering its immediate impact on safety and its broader implications for traffic flow, environmental sustainability, and long-term infrastructure development. The debate around these issues highlights the complexity of road safety improvement efforts, which require a careful balance between engineering solutions, environmental considerations, and the needs of all road users.

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