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Original Article

The Influence of Road Geometry on the Number of Accidents at Curves: A Study on the Variability of Hilliness and Bendiness

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Abstract

This study examined the influence of roadway geometry on traffic safety, focusing on the effects of hilliness and bendiness along a 9.28 km road segment in West Sumatra, Indonesia. Geometric data, including elevation and curvature, were collected using the GeoTracker application and processed with a Python-based sliding window segmentation of 1 km length and 50% overlap, resulting in 19 analysis segments. Traffic accident data were obtained from official police reports and included the number of crashes, minor injuries, serious injuries, and fatalities for each segment. Multivariate Analysis of Variance (MANOVA) was performed to evaluate the simultaneous effects of hilliness and bendiness on the crash variables. The results showed that hilliness significantly influenced the total number of accidents, while bendiness significantly affected the occurrence of serious injuries. Hilliness explained approximately 80% of the variance in accident frequency, and bendiness contributed substantially to variations in serious injuries. Although neither hilliness nor bendiness showed significant effects on minor injuries and fatalities, both factors exhibited positive trends in relation to increasing crash severity. The findings demonstrated that vertical elevation changes and horizontal curvature contributed significantly to traffic accident risks. The study suggested that incorporating these geometric parameters into road design, safety assessments, and targeted interventions could help reduce accident occurrences, particularly in mountainous and curvilinear roadway segments.

Keywords: Traffic Accidents, Hilliness, Bendiness, Sliding Window, MANOVA.

1. Introduction

Road infrastructure has long served as a vital means of fulfilling human mobility and economic needs. The term "road" encompasses not only highways, arterial, or collector roads commonly seen today, but also all types of paths that enable people to move and access various destinations. In the context of transportation systems, roads function as a core element supporting national development, requiring both functional efficiency and operational safety.

Among the various concerns related to road infrastructure, traffic safety remains one of the most critical issues. Road safety is influenced not only by human behavior and vehicle conditions but also by the technical design and construction quality of the road itself (Patiroi, 2022). Poor road design can significantly increase the likelihood of accidents, resulting in injury, loss of life, property damage, and even environmental harm (Susanti et al., 2024). Thus, understanding the interaction between road design and accident occurrence is crucial for improving traffic safety performance (N. A. Farida et al., 2025).

A growing body of research has emphasized the role of geometric road elements in contributing to road safety. Several geometric parameters such as horizontal alignment, vertical alignment, curvature, sight distance, grade, superelevation, and cross-sectional width have been identified as significant factors that influence vehicle stability and driver response (Krammes A & Glascock, 1992). Inconsistent geometric design, particularly on winding and hilly terrains, often leads to increased crash risks due to reduced sight distance, sudden centrifugal forces, and loss of vehicle control (I. Farida & Tanjung, 2022; Mahmudah et al., 2024).

More specifically, road segments with sharp curves (bendiness) and steep gradients (hilliness) present unique safety challenges. Studies have shown that accident frequency can be several times higher at curved sections compared to straight segments, with higher risk levels observed at curves with inappropriate radii or insufficient superelevation (Djoko et al., 2015; Widianty & Karyawan, 2017). These geometric characteristics directly influence vehicle handling dynamics, particularly for heavy vehicles, which may experience speed reductions, rollover risks, and skidding (Al'Adilah et al., 2021; Ruslan & Idham, 2020).

Recent studies have further confirmed the significance of geometric design in minimizing accident risks. Amahoru & Pembuain (2023) and Pradani & Umar (2023) highlighted the importance of ensuring adequate sight distance and curve radii, while Yin et al. (2020) investigated the stability of SUVs on geometrically complex roads. Despite these insights, limited empirical studies have comprehensively investigated the combined effects of hilliness and bendiness on crash risks, particularly on roads with complex topography.

Therefore, this research intends to examine the influence of hilliness and bendiness on road safety, with a particular focus on curved road segments located in hilly areas. The objectives of this study are (i) to analyze how variations in hilliness and bendiness affect crash occurrence, (ii) to provide empirical evidence on the significance of geometric factors in traffic safety performance, and (iii) to offer recommendations for geometric design improvements aimed at reducing accident risks. The findings are expected to contribute to safer road design practices and provide valuable input for policymakers and road engineers in developing more effective safety standards for hilly and winding roads.

2. Literature Review

2.1. Horizontal Alignment

The degree of curve (°) refers to the angle that produces a 25-meter arc length. There is an inverse relationship between the curve radius (R) and the degree of curve (D): as the radius increases, the degree of curve decreases, resulting in a flatter horizontal curve. Conversely, a smaller radius leads to a larger degree of curve, producing a sharper horizontal curve (Nain, 2022). The formula for calculating the degree of curve is as follows:

$$D = \frac{25}{2\pi R} \times 360$$

$$D = \frac{1432{,}39}{R} Degree$$

To maintain vehicle stability while negotiating a curve, a transverse slope known as superelevation (e) is required. On superelevated road sections, lateral friction occurs between the vehicle tires and the road surface, generating lateral friction forces. The ratio between the lateral friction force and the normal force is called the lateral friction coefficient (f). To prevent accidents, the minimum curve radius can be calculated based on a given design speed while considering the maximum allowable superelevation and lateral friction coefficient.

The transition curve (LS) is the curve section located between a straight alignment and a curve with a constant radius (R). Its function is to accommodate the gradual change in road alignment from a straight section (R approaching infinity) to a curve with a defined radius (R), ensuring that the centrifugal force experienced by vehicles changes gradually.

With the inclusion of a transition curve, the horizontal alignment is designed in an S-C-S shape following the spiral curve method based on TPGJAK No.038/T/BM/1997. The length of LS is determined by selecting the maximum value among three criteria: maximum travel time (3 seconds), centrifugal force adjustment, and rate of superelevation change. There are three main types of curves:

a. Full Circle (FC): This curve consists entirely of a circular arc and is typically used for curves with large radii to avoid abrupt directional changes. For small radii, the required superelevation becomes excessively large, making FC curves unsuitable for such conditions.

b. Spiral-Circle-Spiral (SCS): This curve combines a single circular arc with two spiral transitions. It is applied to transition curves where the spiral connects the tangent section to the constant-radius curve. The primary function of this type is to provide a gradual change from tangent to curve alignment. It is suitable for moderate radii and deflection angles (Δ), with the transition curve (LS) connecting the tangent to the spiral curve.

c. Spiral-Spiral (SS): This curve consists only of two spiral sections without a circular arc, meaning that the SC (Spiral to Circle) and CS (Circle to Spiral) points coincide. This curve type is generally applied for large deflection angles (Δ), adapting to complex geometric road requirements.

2.2. Vertical Alignment

Vertical alignment represents the elevation changes along the roadway alignment. This factor is particularly critical in road design for hilly or mountainous areas. Excessive roadway gradients may hinder the ability of heavy vehicles to ascend or descend safely. Therefore, road planning in such regions requires careful consideration of the maximum allowable gradient to ensure the road functions efficiently and safely for all vehicle types.

Gradient also influences travel efficiency. Poor vertical alignment can increase fuel consumption, as vehicles require greater engine power when climbing. Furthermore, excessively steep descents may cause vehicles to lose control, especially if the braking system is not operating optimally. Consequently, special facilities such as climbing lanes, deceleration lanes, or emergency escape ramps are often necessary to mitigate potential accident risks (Nain, 2022).

2.3. Bendiness

Bendiness is a quantitative measure that describes the degree of horizontal curvature along a roadway, typically expressed in total degrees of curvature per kilometer (°/km). Bendiness reflects both the frequency and sharpness of curves within a given road segment. Road sections with high bendiness values generally contain numerous sharp turns or significant directional changes, which can influence driver behavior such as sudden speed reductions, increased braking frequency, and elevated crash risk due to loss of control while negotiating curves.

In the context of traffic engineering and road safety, bendiness is employed to evaluate both driver comfort and safety, as well as to support the placement of warning signs, guardrails, and appropriate speed limits. Bendiness can be calculated using the following formula:

$$Bendiness = \frac{\sum \text{Curve Angles}}{Segment\ Length}$$

Previous studies, such as that conducted by Cafiso et al. (2007), have shown that sharp curves located closely together significantly increase crash frequency, particularly on secondary roads and in complex terrain. Bendiness has also been utilized as a predictor variable in both macroscopic and microscopic safety models, where high curvature degrees are associated with an increased likelihood of traffic conflicts. Austroads (2016), in its design guidelines, further emphasizes that extreme horizontal curvature requires special consideration in geometric design due to its direct impact on vehicle stability and drivers' risk perception.

2.4. Hilliness

Hilliness is a measure that describes the degree of vertical elevation change along a road alignment per unit of horizontal distance, typically expressed in meters per kilometer (m/km). This indicator is crucial in transportation studies as it directly affects vehicle performance, fuel consumption, operational speed, and traffic safety. Roads with high hilliness values often feature steep ascents and descents that may lead to loss of vehicle control, particularly under adverse weather conditions or when operated by inexperienced drivers. Moreover, extreme elevation changes affect driver visibility and reaction time, thereby increasing the overall risk of crashes. As such, hilliness is frequently incorporated into various road safety models and infrastructure planning frameworks to identify high-risk road segments. The formula for calculating hilliness is as follows:

$$Hilliness = \frac{\sum \text{Elevation Differences}}{\text{Segment Length}}$$

Several studies have integrated hilliness into crash prediction or road risk assessment models, such as within Road Safety Inspection (RSI) frameworks or crash prediction models based on geometric characteristics. According to the Austroads Guide to Road Safety, sharp elevation variations are significantly associated with increased crash frequency and severity on intercity and mountainous roads. Furthermore, research by Turner et al. (2017) highlights that routes with complex vertical profiles require special design treatments, including the addition of warning signage, adaptive speed limits, and emergency braking facilities for heavy vehicles

2.5. Sliding Moving Window

Sliding window is a data segmentation method used to analyze phenomena either spatially or temporally by dividing the observation path into overlapping segments. In the context of roadway analysis and traffic safety, this approach enables continuous monitoring of roadway characteristics such as grade, curvature, or surface parameters, in contrast to fixed-interval segmentation methods that often overlook transitions between segments. According to Qu et al. (2015), the sliding window technique provides higher spatial sensitivity for risk location detection as it can capture small geometric variations that may be missed by non-overlapping segmentation approaches.

In transportation studies, this method has been applied to measure geometric parameters such as curvature, grade, and alignment consistency, with direct applications in black spot evaluation and road design. For example, Al-Janabi et al. (2020) applied the sliding window approach to estimate the road curvature index and link it to crash probability on winding roads. Their results demonstrated that overlapping segmentation yields higher accuracy in identifying critical locations compared to conventional segmentation methods.

By utilizing a fixed window size and a specific step size, the sliding window technique allows for smoother integration between spatial parameters and crash occurrence data and supports continuous spatial analysis such as geographically weighted regression (GWR).

3. Methods

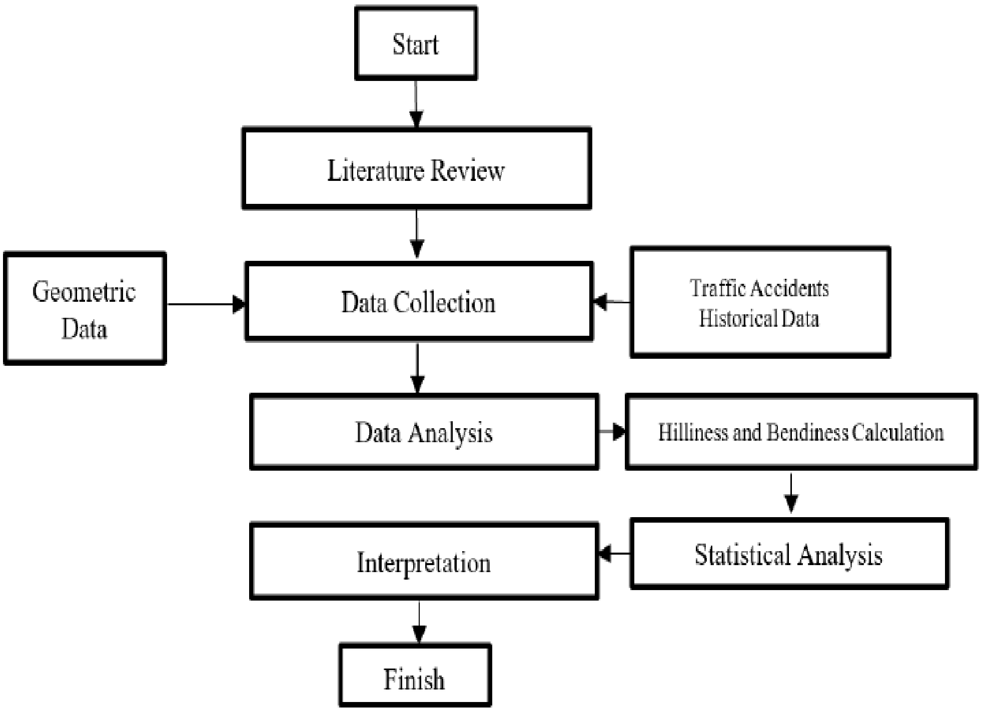


Figure 1. Research Flowchart

This research is conducted along the curved segments of the Padang–Bukittinggi Road located in West Sumatra Province, specifically spanning 9.28 kilometres within the administrative regions of Padang Panjang and Padang Pariaman. The selected study area features a combination of challenging road geometry, making it suitable for examining traffic safety conditions associated with curvatures and gradients.

One of the primary considerations in selecting this location is the diversity of geometric road characteristics, particularly in terms of hilliness and bendiness across multiple curves. These variations allow for comprehensive evaluation of how these factors influence the frequency and severity of traffic accidents. The natural changes in elevation and turning angles along the road provide a dynamic environment for analysing the interaction between road geometry and driver behaviour. In addition to its geometric features, the selected road segment has a relatively complete and well-documented record of traffic accidents. The availability of secondary data on the number of crashes, fatalities, minor injuries, and serious injuries supports the accuracy and validity of the study. This reliable dataset ensures a more precise statistical analysis and reinforces the significance of the research findings in evaluating geometric safety performance.

3.1. Primary Data Collection

Figure 2. Survey Illustration

To measure the average vehicle speed at the observation site, a straight road segment of 163.35 meters was used, beginning from the point before the vehicle entered the designated survey area. The observation was carried out by recording the travel time of each vehicle along this segment using a static camera. The segment length was measured in meters, while the time was recorded in seconds. The average speed was then calculated using the basic formula of dividing distance by time, providing the initial velocity of vehicles as they approached the crossing area.

This speed measurement was conducted as part of a one-hour traffic survey session on May 6, 2025, during both the morning and evening peak hours. The objective of this assessment was to capture a comprehensive overview of driver behaviour in terms of speed when approaching the crossing zone. By understanding actual speed patterns, the study aimed to evaluate traffic performance and identify potential risks. These findings can be used to determine whether additional traffic engineering interventions are needed to improve safety at the location.

Table 1. Traffic Volume at Segment Study

Time Window	A					B				
	Motorcycle	Car	Pickup/Box	Bus	Truck	Motorcycle	Car	Pickup/Box	Bus	Truck
Morning Peak Hour										
0 - 15	30	42	7	8	15	47	31	5	5	10
15-30	46	43	6	6	8	59	37	4	3	5
31-45	38	47	6	9	14	30	17	2	3	10
45-60	39	48	2	6	20	23	21	7	4	3
Evening Peak Hour										
0 - 15	33	27	2	3	10	55	45	8	0	13
15-30	45	41	20	4	9	50	35	2	3	14
31-45	35	55	12	4	5	38	34	7	4	16
45-60	56	45	11	3	4	53	69	11	4	9

Based on the survey conducted during one hour of peak traffic in both the morning and evening, traffic volume data was collected for vehicles passing through the study segment. In the evening, motorcycles were the most common vehicle type, with a total of 343 vehicles recorded, followed by private cars with 202 vehicles. Other vehicle types such as trucks, pick-ups/box trucks, and buses were observed in significantly smaller numbers. In the morning, overall traffic volume was relatively lower than in the evening, with motorcycles still dominating, while larger vehicles such as buses and trucks appeared in limited quantities.

In terms of average speed, observations showed that motorcycles had the highest speed at 53.8 km/h, followed by private cars at 48.3 km/h. Pick-ups/box trucks and buses recorded moderate speeds of 42.8 km/h and 44.4 km/h, respectively. Trucks had the lowest average speed at 37.9 km/h. These findings indicate that private vehicles, particularly motorcycles and cars, not only dominate traffic volume but also tend to travel faster than freight and passenger transport vehicles.

The primary data collection for the parameters of hilliness and bendiness was conducted using the GeoTracker application installed on a mobile phone device. This application operates based on GPS tracking principles, automatically recording route coordinates along with elevation (altitude) values at each point during the journey. The data captured includes spatial information in the form of the vehicle's travel path and elevation differences between points, which is highly beneficial for analysing the longitudinal geometric characteristics of the road.

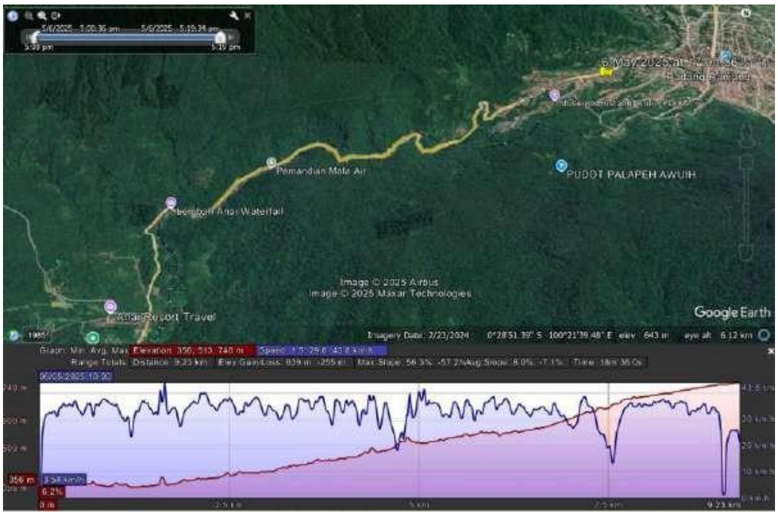


Figure 3. Geometric Data at Segment Study

The survey was carried out by a surveyor who travelled the 9.28 km road segment using a car at an average speed of approximately 40 km/h, following the same lane to be analyzed. During the journey, GeoTracker continuously recorded the path with high data resolution, producing accurate elevation profiles and road curvature data. The recorded coordinates and elevation were then used to calculate hilliness defined as the elevation change per kilometre, and bendiness defined as the total directional change or angular deviation per kilometre of road length.

3.2. Secondary Data Collection

The secondary traffic accident data used in this study were obtained from official reports issued by the Traffic Units (SATLANTAS) of Padang Panjang Police Department and Padang Pariaman Police Department, both operating under the coordination of the West Sumatra Regional Police (POLDA Sumatera Barat). The collected reports document traffic accidents that occurred along the study corridor, including report numbers, the number of victims, and injury severity classifications (minor injuries, serious injuries, and fatalities). These data were utilized to analyze the spatial distribution of accidents along the study route.

Table 2. Traffic Accidents Data at Segment Study

Segment	Total of Traffic Accidents at Segment	Total of Minor Injuries	Total of Serious Injuries	Total of Fatalities
1	1	1	0	0
2	0	0	0	0
3	1	2	0	0
4	1	0	0	0
5	1	0	0	1
6	1	0	0	1
7	1	0	0	1
8	1	0	0	1
9	6	2	0	0
		1	0	0
		4	0	0
		0	0	2
		1	0	0
		2	0	0
10	5	1	0	0
		6	0	1
		0	1	0
		2	0	0
		2	0	0
11	0	0	0	0
12	2	1	0	0
		0	0	1
13	1	39	0	0
14	1	1	0	0
15	5	1	0	0
		0	0	1
		1	0	0
		1	0	0
		1	0	0
16	3	12	1	0
		1	0	0
		1	0	0
17	3	1	0	0
		1	0	0
		2	0	0
18	4	1	0	1
		1	0	0
		1	0	0
		3	0	0
19	3	1	0	0
		2	0	0
		2	0	0

To facilitate more detailed spatial analysis and capture finer geographic dynamics, the 9.28-kilometer road section was divided into 19 segments using an overlapping sliding window approach with a window size of 1 km and a step size of 500 meters. In this method, each segment is 1 km long but overlaps with the preceding or following segment by 500 meters. This approach allows for a more continuous evaluation of road geometric characteristics and accident distribution, avoiding the abrupt segment boundaries inherent in conventional 1-km fixed segmentation.

Using this overlapping approach, a total of 38 traffic accident cases were identified across the 19 segments. These incidents involved 104 minor injuries, 2 serious injuries, and 9 fatalities. The overlapping segmentation method demonstrated higher sensitivity in capturing accident distribution patterns related to roadway conditions, as it reflects the cumulative effects of adjacent segments. For example, both segment 8 (3500–4500 m) and segment 9 (4000–5000 m) recorded a high number of accidents, including multiple fatalities and minor injuries, indicating that the area between 3500 and 5000 meters constitutes a high-risk crash cluster.

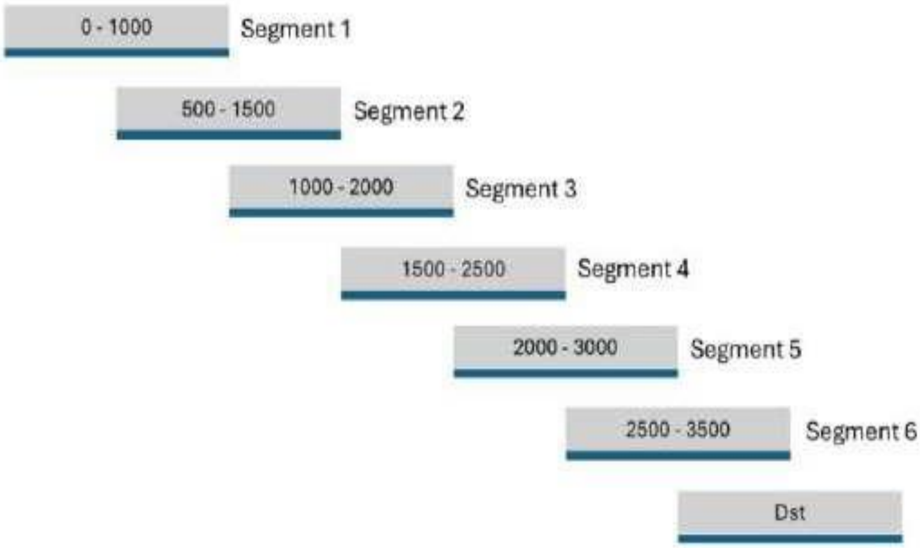


Figure 4. Sliding Moving Window Illustration

The sliding moving window proved highly effective in identifying critical zones that may have been overlooked using rigid 1-km segmentation. Based on these findings, the study was able to map accident-prone areas with greater alignment to real-world road conditions and traffic behavior. This enables policymakers and traffic engineers to develop more accurate and location-based safety interventions, such as the installation of warning signs, geometric improvements, or speed restrictions at strategically identified high-risk locations.

3.3. Hilliness and Bendiness Analysis

The processing of GeoTracker data to calculate hilliness and bendiness was carried out systematically using Python. Python was chosen due to its robust libraries such as pandas, geopy, numpy, and math, which are well-suited for spatial and numerical analysis. Data exported from GeoTracker in .csv format were imported into Python using pandas to manage them as dataframes. The dataset includes key variables such as latitude, longitude, and elevation, which were cleaned to remove missing values and inconsistencies to ensure the accuracy of the computations.

Hilliness was calculated by summing the absolute elevation differences between consecutive points and dividing by the total route length (km), using the geodesic() function from the geopy library. Bendiness was computed by forming directional vectors from every three consecutive GPS points and calculating the angle between them using the dot product and atan2() from Python's math library. Both metrics were normalized per kilometer. To enhance analysis, the road was divided into 1-km segments, with hilliness and bendiness calculated separately for each. Results were exported to Excel/CSV for further analysis in SPSS, enabling robust, geometry-based road safety assessments.

Table 3. Hilliness and Bendiness Value at Each Segment

Segment	Hilliness (m/km)	Bendiness (°/km)
0-500 m	36,23	284,13
500-1000 m	39,09	369,7
1000-1500 m	38,18	408,43
1500-2000 m	51,82	343,32
2000-2500 m	48,78	90,34
2500-3000 m	37,61	87,99
3000-3500 m	50,35	140,14
3500-4000 m	95,16	316,41
4000-4500 m	31,03	339,3
4500-5000 m	64,98	925,44
5000-5500 m	103,64	504,69
5500-6000 m	41,22	496,39
6000-6500 m	44,68	212,83
6500-7000 m	84,7	469,69
7000-7500 m	90,11	575,47
7500-8000 m	54,31	207,28
8000-8500 m	55,32	84,75
8500-9000 m	59,31	213,68
9000-9280 m	28,3	193,47

Primary data on elevation and coordinates were collected using the GeoTracker application along the 9.28-kilometer road segment that served as the study area. The recorded data were subsequently processed using a custom-developed Python script that applied a sliding window segmentation approach with a window size of 1 km and 50% overlap. In this approach, each new segment starts 500 meters after the previous segment's starting point, resulting in a total of 19 analysis segments covering 0–1000 m up to 9000–9280 m. This method allows for a more refined and continuous capture of geometric variations compared to conventional non-overlapping segmentation.

Hilliness values were calculated by summing the absolute elevation differences between consecutive points within each segment and dividing by the segment length in kilometers. This value represents the vertical fluctuation experienced by vehicles within each segment. For example, the segment from 6500 to 7500 meters exhibited the highest hilliness value of 88.71 m/km, indicating the presence of significant ascents or descents that may elevate crash risk due to reduced visibility or vehicle load constraints.

Meanwhile, bendiness was calculated by summing the total turning angles derived from every consecutive set of three coordinate points, expressed in degrees per kilometer (°/km). This computation was conducted using a vector-based trigonometric method. The highest bendiness value was observed in the segment from 4500 to 5500 meters, with a bendiness of 734.39°/km, indicating the possible presence of multiple sharp curves that may lead to traffic conflicts, especially in the absence of appropriate warning signs or speed regulations.

By implementing the 1-km overlapping sliding window approach, more detailed information was obtained regarding elevation and curvature patterns along the study route. This method enables more accurate and responsive spatial analysis aligned with actual roadway conditions and facilitates the identification of critical segments requiring safety engineering interventions. Additionally, the approach supports further statistical analysis, such as correlating geometric characteristics with crash data to evaluate their direct influence on traffic safety.

3.4. Statistical Analysis

Table 4. Research Variables

Variable	Code	Data
Y1	JumlahLAKA	Total of Traffic Accidents
Y2	JumlahLR	Total of Minor Injuries
Y3	JumlahLB	Total of Serious Injuries
Y4	JumlahLB	Total of Fatalities
X1	Bendiness	Bendiness
X2	Hilliness	Hilliness
X3	MSMotor	Mean Speed Motorcycle
X4	MSMobil	Mean Speed Car
X5	MSPickupBox	Mean Speed Pick-Up/Box
X6	MSBus	Mean Speed Bus
X7	MSTruck	Mean Speed Truck

The dependent variables in this research consist of four key indicators: the total number of accidents in each road segment (JumlahLAKA/Y1), the number of minor injuries (JumlahLR/Y2), the number of serious injuries (JumlahLB/Y3), and the number of fatalities (JumlahMD/Y4). These variables are derived from official traffic accident records compiled by the police and are distributed across ten segments along the study corridor.

The independent variables are grouped into two categories. The first includes geometric variables that describe the physical features of the road: Bendiness (X1), which indicates the degree of road curvature in degrees per kilometer, and Hilliness (X2), which reflects the change in elevation in meters per kilometer. These variables are calculated using Python from GPS and elevation data collected by the GeoTracker mobile application, which tracks the vehicle's path and elevation changes throughout the journey.

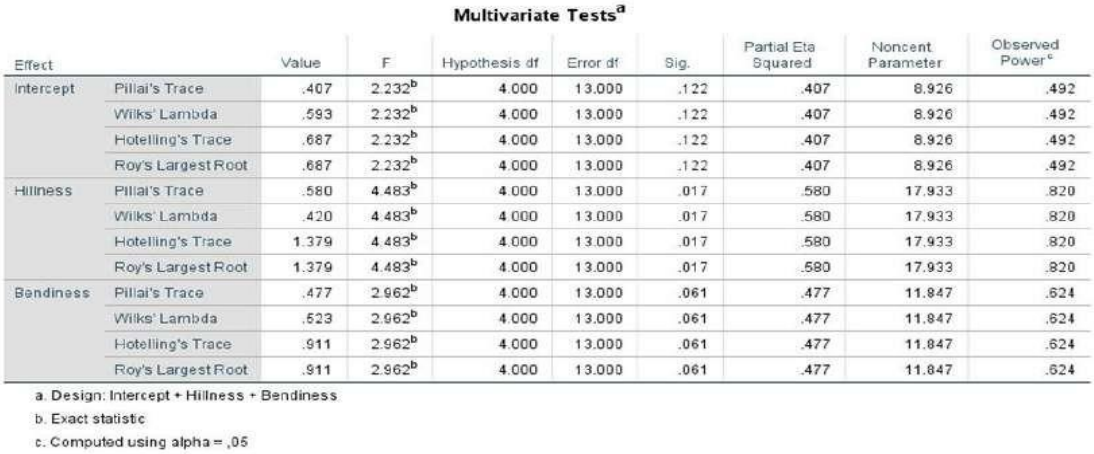
The second group of independent variables focuses on the average speed of different vehicle types, which are measured per segment. These include MSMotor (X3) for motorcycles, MSMobil (X4) for passenger cars, MSPickupBox (X5) for light goods vehicles, MSBus (X6) for buses, and MSTruck (X7) for trucks. These speeds are obtained through direct field observations using video footage and time measurements with a stopwatch. The collected data allows for the calculation of average speed by dividing the length of the travel path by the time taken, ensuring accurate speed profiling for each vehicle type across all segments.

All these variables were entered into Statistical Package for the Social Sciences (SPSS) in both numerical and nominal formats and were utilized in various statistical analyses, including Multivariate Analysis of Variance (MANOVA), to examine the relationships and effects of the independent variables on accident rates across each road segment. The use of symbolic labelling such as Y1, X1 through X7 was also intended to facilitate the reading of statistical models and the formulation of equations during the interpretation of the analysis results.

4. Results and Discussion

A Multivariate Analysis of Variance (MANOVA) was conducted to evaluate whether there were simultaneously significant differences across four dependent variables, Number of Accidents, Number of Minor Injuries, Serious Injuries, and Fatalities based on two primary independent variables, Hilliness and Bendiness. The variables X3 through X7 exhibited identical values across all segments, as average vehicle speed data were only available from a single observation point. This limitation resulted in no variation across segments for these variables, rendering them statistically redundant and unsuitable for inclusion in the multivariate model. Consequently, vehicle speeds by vehicle type were treated solely as supporting information and were excluded from inferential testing or parameter estimation in the primary model.

Table 5. SPSS Result for Multivariate Tests



Multivariate Tests^{a}

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power^{c}
Intercept	Pillai's Trace	.407	2.232^{b}	4.000	13.000	.122	.407	8.926	.492
	Wilks' Lambda	.593	2.232^{b}	4.000	13.000	.122	.407	8.926	.492
	Hotelling's Trace	.687	2.232^{b}	4.000	13.000	.122	.407	8.926	.492
	Roy's Largest Root	.687	2.232^{b}	4.000	13.000	.122	.407	8.926	.492
Hillness	Pillai's Trace	.580	4.483^{b}	4.000	13.000	.017	.580	17.933	.820
	Wilks' Lambda	.420	4.483^{b}	4.000	13.000	.017	.580	17.933	.820
	Hotelling's Trace	1.379	4.483^{b}	4.000	13.000	.017	.580	17.933	.820
	Roy's Largest Root	1.379	4.483^{b}	4.000	13.000	.017	.580	17.933	.820
Bendiness	Pillai's Trace	.477	2.962^{b}	4.000	13.000	.061	.477	11.847	.624
	Wilks' Lambda	.523	2.962^{b}	4.000	13.000	.061	.477	11.847	.624
	Hotelling's Trace	.911	2.962^{b}	4.000	13.000	.061	.477	11.847	.624
	Roy's Largest Root	.911	2.962^{b}	4.000	13.000	.061	.477	11.847	.624

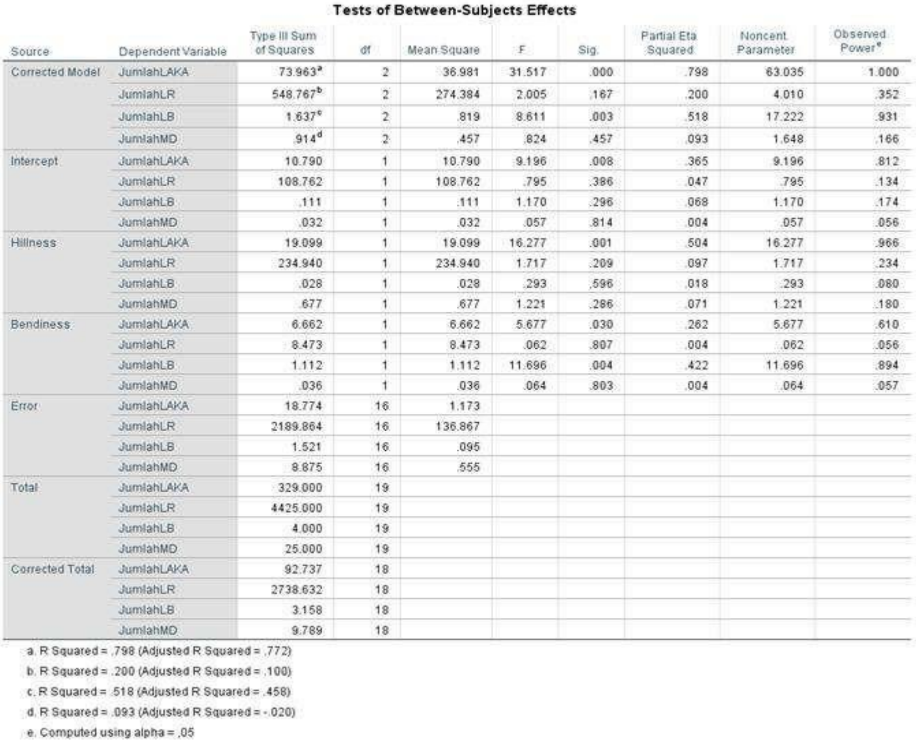
a. Design: Intercept + Hillness + Bendiness

b. Exact statistic

c. Computed using alpha = ,05

According to the results of the Multivariate Tests, the independent variable Hilliness yielded a significance value of 0.017, while Bendiness produced a significance value of 0.061. These results indicate that Hilliness has a statistically significant multivariate effect on the set of dependent variables at the 5% significance level, while Bendiness exhibits a near-significant effect. Furthermore, the relatively high Partial Eta Squared values (Hilliness = 0.580; Bendiness = 0.477) suggest that both variables contribute substantially to the observed variation in the data.

Table 6. SPSS Result for Tests of Between Subjects Effects



Tests of Between-Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power^{e}
Corrected Model	JumlahLAKA	73.963^{a}	2	36.981	31.517	.000	.798	63.035	1.000
	JumlahLR	548.767^{b}	2	274.384	2.005	.167	.200	4.010	.352
	JumlahLB	1.637^{c}	2	.819	8.611	.003	.518	17.222	.931
	JumlahMD	.914^{d}	2	.457	.824	.457	.093	1.648	.166
Intercept	JumlahLAKA	10.790	1	10.790	9.196	.008	.365	9.196	.812
	JumlahLR	108.762	1	108.762	.795	.386	.047	.795	.134
	JumlahLB	.111	1	.111	1.170	.296	.068	1.170	.174
	JumlahMD	.032	1	.032	.057	.814	.004	.057	.056
Hillness	JumlahLAKA	19.099	1	19.099	16.277	.001	.504	16.277	.966
	JumlahLR	234.940	1	234.940	1.717	.209	.097	1.717	.234
	JumlahLB	.028	1	.028	.293	.596	.018	.293	.080
	JumlahMD	.677	1	.677	1.221	.286	.071	1.221	.180
Bendiness	JumlahLAKA	6.662	1	6.662	5.677	.030	.262	5.677	.610
	JumlahLR	8.473	1	8.473	.062	.807	.004	.062	.056
	JumlahLB	1.112	1	1.112	11.696	.004	.422	11.696	.894
	JumlahMD	.036	1	.036	.064	.803	.004	.064	.057
Error	JumlahLAKA	18.774	16	1.173					
	JumlahLR	2189.864	16	136.867					
	JumlahLB	1.521	16	.095					
	JumlahMD	8.875	16	.555					
Total	JumlahLAKA	329.000	19						
	JumlahLR	4425.000	19						
	JumlahLB	4.000	19						
	JumlahMD	25.000	19						
Corrected Total	JumlahLAKA	92.737	18						
	JumlahLR	2738.632	18						
	JumlahLB	3.158	18						
	JumlahMD	9.789	18						

a. R Squared = ,798 (Adjusted R Squared = ,772)

b. R Squared = ,200 (Adjusted R Squared = ,100)

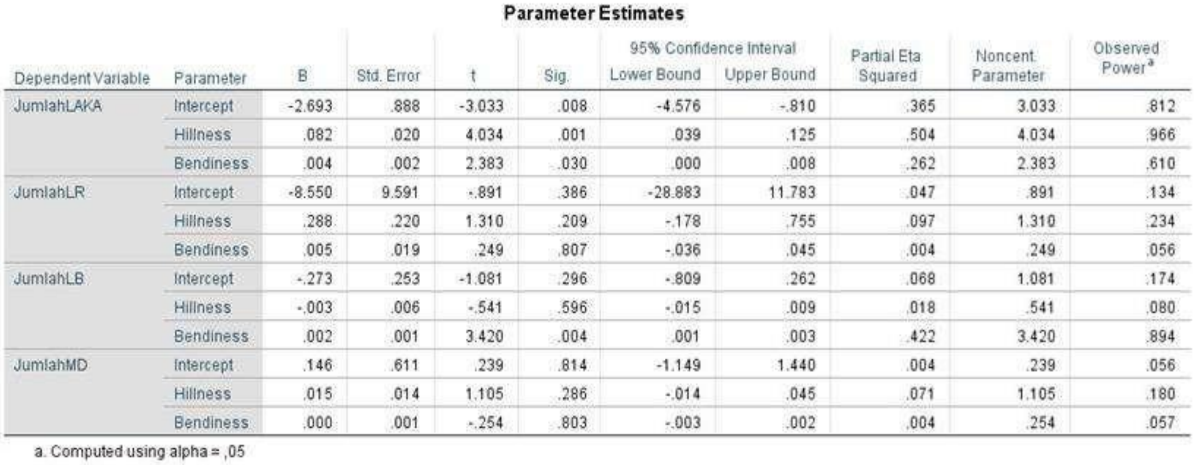
c. R Squared = ,518 (Adjusted R Squared = ,458)

d. R Squared = ,093 (Adjusted R Squared = -,020)

e. Computed using alpha = ,05

Further testing using the Tests of Between-Subjects Effects revealed that Hilliness had a statistically significant effect on the Number of Accidents (Sig. = 0.001), with an R-squared value of 0.798, indicating that this variable explains nearly 80% of the variation in accident frequency. Bendiness also demonstrated a significant effect on the Number of Accidents (Sig. = 0.030), with a Partial Eta Squared value of 0.262. Although neither Hilliness nor Bendiness exhibited statistically significant effects on the other dependent variables — Number of Minor Injuries, Serious Injuries, and Fatalities — the Partial Eta Squared values for these variables still suggest a potential contribution to the observed data variation.

Table 7. SPSS Result for Parameter Estimates



Parameter Estimates

Dependent Variable	Parameter	B	Std. Error	t	Sig.	95% Confidence Interval		Partial Eta Squared	Noncent. Parameter	Observed Power^{a}
						Lower Bound	Upper Bound			
JumlahLAKA	Intercept	-2.693	.888	-3.033	.008	-4.576	-.810	.365	3.033	.812
	Hillness	.082	.020	4.034	.001	.039	.125	.504	4.034	.966
	Bendiness	.004	.002	2.383	.030	.000	.008	.262	2.383	.610
JumlahLR	Intercept	-8.550	9.591	-.891	.386	-28.883	11.783	.047	.891	.134
	Hillness	.288	.220	1.310	.209	-.178	.755	.097	1.310	.234
	Bendiness	.005	.019	.249	.807	-.036	.045	.004	.249	.056
JumlahLB	Intercept	-.273	.253	-1.081	.296	-.809	.262	.068	1.081	.174
	Hillness	-.003	.006	-.541	.596	-.015	.009	.018	.541	.080
	Bendiness	.002	.001	3.420	.004	.001	.003	.422	3.420	.894
JumlahMD	Intercept	.146	.611	.239	.814	-1.149	1.440	.004	.239	.056
	Hillness	.015	.014	1.105	.286	-.014	.045	.071	1.105	.180
	Bendiness	.000	.001	-.254	.803	-.003	.002	.004	.254	.057

a. Computed using alpha = ,05

Based on the parameter estimates for the dependent variable Number of Accidents, both Hilliness and Bendiness exhibited positive and statistically significant effects on accident frequency. The regression coefficient for Hilliness was 0.082 (p = 0.001), indicating that for each one-unit increase in hilliness (m/km), the number of accidents is predicted to increase by 0.082 cases, holding other variables constant. This effect is relatively strong, with a Partial Eta Squared of 0.504, suggesting that hilliness accounts for more than 50% of the variance in accident frequency within the model. Meanwhile, Bendiness had a regression coefficient of 0.004 (p = 0.030), with a Partial Eta Squared of 0.262, indicating a statistically significant but relatively smaller effect compared to Hilliness. Overall, both roadway elevation and curvature contribute significantly to accident occurrence.

For the Number of Minor Injuries, both Hilliness (B = 0.288) and Bendiness (B = 0.005) showed positive regression coefficients, suggesting a tendency for increases in elevation or curvature to raise the number of minor injuries. However, the significance levels for Hilliness (p = 0.209) and Bendiness (p = 0.807) indicate that these relationships are not statistically significant. The very low Partial Eta Squared values further suggest weak effect sizes. These results imply that increases in hilliness and bendiness have not shown consistent statistical effects on minor injury occurrences, likely due to high variability in minor injury data across segments or the influence of other factors such as speed, weather conditions, or the use of personal safety devices.

For the Number of Serious Injuries, Hilliness had a very small positive coefficient of 0.003 (p = 0.596), while Bendiness exhibited a coefficient of 0.032 (p = 0.004). Thus, only Bendiness demonstrated a statistically significant effect on serious injury counts. The coefficient of 0.032 indicates that each one-unit increase in bendiness (degrees/km) is associated with an increase of 0.032 serious injury cases. With a Partial Eta Squared of 0.422, this effect can be classified as moderate to large. Conversely, Hilliness did not contribute meaningfully to serious injuries. This finding emphasizes that highly curved roadways pose a greater risk of serious injury, likely due to sharper vehicle maneuvers and reduced vehicle stability when negotiating curves.

For the Number of Fatalities, the analysis showed that neither Hilliness (B = 0.015; p = 0.286) nor Bendiness (B = 0.000; p = 0.803) had statistically significant effects on fatal crash outcomes. Although Hilliness displayed a positive coefficient suggesting that increased elevation might be associated with elevated fatality risk, the relationship was not strong enough to be statistically conclusive. The low variability in fatality counts within the dataset is likely a major factor contributing to the non-significant results. With very low Partial Eta Squared values for both independent variables, it can be concluded that these variables do not adequately explain fatality variation within the context of this model.

5. Conclusion

Based on the results of the present study conducted along a 9.28 km road segment using 1-km overlapping segmentation, substantial variation was observed in both hilliness and bendiness across segments. The maximum hilliness reached 873.48 m/km, while the maximum bendiness recorded was 609.98°/km, indicating sharp elevation changes and horizontal curvature in certain parts of the road. Statistical analysis using MANOVA and Parameter Estimates in SPSS identified that hilliness had a significant effect on the total number of accidents (p = 0.001), while bendiness significantly influenced the number of serious injuries (p = 0.004).

These findings suggest that extreme elevation changes may directly increase accident frequency, potentially due to loss of vehicle control, reduced visibility, and unstable speed fluctuations. On the other hand, sharp horizontal curvature tends to elevate the risk of serious injuries, particularly when drivers fail to appropriately adjust speed to match curvilinear road conditions. Although not all associations with minor injuries and fatalities reached statistical significance, both hilliness and bendiness demonstrated positive contributions within the predictive models.

This study highlights the critical role of roadway geometric parameters specifically hilliness and bendiness in crash risk analysis. By incorporating these indicators into roadway design processes, safety audits, and technical decision-making, stakeholders can more accurately identify high-risk locations and implement more effective interventions, such as speed adjustments, installation of warning signs, or geometric realignments on critical segments.

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6. References

Al-Janabi, S., Mohammad, M., & Al-Sultan, A. (2020). A new method for prediction of air pollution based on intelligent computation. *Soft Computing*, *24*(1), 661–680.

Al'Adilah, Hasanuddin, A., & Kriswardhana, W. (2021). Analisis Pengaruh Geometrik Jalan

Terhadap Keselamatan Lalu Lintas di Jalan Bypass Mojokerto KM Surabaya (SBY) 51-63. *Paduraksa*, *10*(2).

Amahoru, J., & Pembuain, A. (2023). Analisis Pengaruh Geometrik Jalan Terhadap Jarak Pandang Pengendara dalam Mencegah Kecelakaan Lalu Lintas (Studi Kasus: Jalan Mangga Dua Kecamatan Nusaniwe Kota Ambon). *Manumata: Jurnal Ilmu Teknik*, *9*(2), 147–153.

Austroads, N. T. C. (2016). *Assessing Fitness to Drive for Commercial and Private Vehicle Drivers: Medical Standards for Licensing and Clinical Management Guidelines*. Https://Austroads.Gov.Au/Publications. https://www.onlinepublications.austroads.com.au/items/AP-G56-16

Cafiso, S., La Cava, G., & Montella, A. (2007). Safety index for evaluation of two-lane rural highways. *Transportation Research Record*, *2019*(1), 136–145.

Djoko, P., Amelia, K. I., & Kami, H. B. (2015). Hubungan antara Kecepatan dan Kondisi Geometrik Jalan yang Berpotensi Menyebabkan Kecelakaan Laalu Lintas pada Tikungan. *Jurnal Ilmu Terapan Bidang Teknik Sipil*, *21*(2), 83–90.

Farida, I., & Tanjung, F. (2022). Analisis Kondisi Geometrik Jalan Terhadap Potensi Kecelakaan Lalu Lintas Kendaraan Roda Empat. *Jurnal Konstruksi*, *19*(2). https://doi.org/10.33364/konstruksi/v.19-2.998

Farida, N. A., Nugroho, L. D., & Muhammadun, H. (2025). Road Handling Priority Analysis Using Provincial/District Roads Management System Application and Analytical Hierarchy Process Method. *INTERNATIONAL JOURNAL ON ADVANCED TECHNOLOGY, ENGINEERING, AND INFORMATION SYSTEM*, *4*(1), 26–39. https://doi.org/10.55047/ijateis.v4i1.1567

Krammes A, R., & Glascock, S. W. (1992). Geometric inconsistencies and accident experience on two-lane rural highways. *Paper Presented at the 71st Annual Meeting of the Transportation Research Board, Washington, DC, August 1991 ., 1356*.

Mahmudah, N., Reswara, H., & Al-Haji, G. (2024). Analisis Hubungan Geometrik Jalan dengan Potensi Kecelakaan di Jalan Imogiri-Dlingo, Bantul, Indonesia. *Media Komunikasi Teknik Sipil*, *29*(2), 271–279.

Patiroi, A. (2022). Kajian Aspek Keselamatan Jalan Terhadap Jalan Daerah Kabupaten Tana Toraja Untuk Mendukung Kegiatan Ekonomi Dan Pariwisata. *Jurnal Keselamatan Transportasi Jalan (Indonesian Journal of Road Safety)*, *9*(1). https://doi.org/10.46447/ktj.v9i1.429

Pradani, A. R., & Umar, U. H. (2023). The Road Geometric Design of Jalan Weleri-Patean (65+ 850-67+ 850). *LEADER: Civil Engineering and Architecture Journal*, *1*(3), 302–308.

Ruslan, R., & Idham, M. (2020). Penentuan Jenis Tikungan Dan Geometrik Jalan (Studi Kasus: Jalan Kayu Api Kuala Penaso, Kecamatan Talang Muandau). *Jurnal TeKLA*, *2*(2). https://doi.org/10.35314/tekla.v2i2.1820

Susanti, N., Angkat, C. T. D. E., Pohan, D. A., & Nasution, M. (2024). Analisis Faktor–Faktor Yang Berhubungan Dengan Resiko Kecelakaan Lalu Lintas. *Jurnal Kesehatan Tambusai*, *5*(2), 5423–5429.

Turner, B., Jurewicz, C., & Makwasha, T. (2017). What works when providing safe road infrastructure?: 10 treatments that need to be used more. *Road & Transport Research: A Journal of Australian and New Zealand Research and Practice*, *26*(3), 36–45.

Widianty, D., & Karyawan, I. D. M. A. (2017). Karakterisasi Peluang Dan Resiko Kecelakaan Lalu Lintas Pada Beberapa Segmen Ekstrim Ruas Jalan Senggigi-Pemenang: Characterization Opportunities and Risk of Traffic Accident on some Extreme Segments of the Senggigi-Pemenang Road. *Spektrum Sipil*, *4*(2), 142–150.

Yin, Y., Wen, H., Sun, L., & Hou, W. (2020). The influence of road geometry on vehicle rollover and skidding. *International Journal of Environmental Research and Public Health*, *17*(5), 1648.