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Traffic Accident Spatial Modeling Using Adaptive Kernel Density Estimation Method Based on Geographical Information Systems For Road Sections In Brebes District, Brebes Regency

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Abstract

Based on information from the Satlantas Polres Bebes, in 2022 the number of accidents in the Brebes Regency area reached 1.088 incidents that cause fatality damage and material losses. Data shows that in the last three years, Brebes District has recorded as the district with the highest accident statistics in this region. These incidents have a tendency to occur in certain sections. This research using a Geographic Information System (GIS) based approach using the Adaptive Kernel Density Estimation method to analyze the density of accidents on the road sections. The road network is divided into segments of 1000 meters and sub-segments iterated every 20 meters to obtain more accurate results. Vulnerability maps are classified based on the weighting of accident frequency, blackspot maps are classified based on Equivalent Accident Number (EAN) calculation. The results of the accuracy test comparison show that the Adaptive Kernel Density Estimation method can produce a vulnerability maps model with suitability level accuracy of 71,13%. In blackspot modeling, the CPAI calculation results show that the Adaptive Kernel Density Estimation method can produce a CPAI index of 71,73%.

Keywords: *Traffic Accidents, Density Analysis, Adaptive Kernel Density Estimation, Equivalent Accident Number (EAN), Crash Predictive Accuracy Index (CPAI).*

1. Introduction

Brebes Regency is an area in Central Java located at 6°44'56.50” - 7°20'51.48”S and 108°41'37.70” - 109 °11'28.92”E. Geographically located at Pantura Route makes this area very crucial in connecting transportation networks between regions. The high volume of mobility indirectly has an impact on improving the traffic accident algorithm. Based on data from the Satlantas Polres Brebes, in 2022 the number of accidents in the Brebes Regency area reached 1.088 incidents incidents that cause fatality damage and material losses. For the last three years, Brebes District has recorded as the district with the highest accident statistics in this region. The number is around 70 incidents in 2020, 101 incidents in 2021, and 104 incidents in 2022. These incidents tend to occur on certain sections.

According to information from Satlantas Polres Brebes, there has not been a spesific approach and research has been carried out on the road sections with the highest frequency of accidents. It is difficult for the police to monitor areas with the potential to become accident spots. Based on these problems, strategic need to be made to decrease incidents number. One of the preventive action that can be taken is by identify accident vulnerabilities and blackspots.

A Geographic Information System (GIS) based approach can be used to analyze the density of accidents on these road sections. Vulnerability locations are parts of roads that have a high number of accidents and tend to recur at certain time intervals. Blackspots are points on traffic accident-prone sections that have a high level of accidents in a certain period of time based on the weight of fatalities and estimates of material losses incurred (Mielarich, 2016). GIS method that can be used to estimate accident vulnerabilty locations and traffic accident blackspots is using density-based clustering process.

Kernel Density Estimation (KDE) is a method that can be used to calculate density estimates. According to research conducted by (Gelb, 2021), the classic KDE method has shortcomings when used to model accidents because it performs calculations based on area size. On the other hand, traffic accident occurs on roads that categorized into the network data so the classic KDE method is not suitable for this case implementation. Therefore, (Gelb, 2021) carry out estimates using the Network Kernel Density Estimation method to overcome this problem. The Adaptive Kernel Density Estimation method is a complex development of the Network Kernel Density Estimation method with adaptive bandwidth search. This method can be used to vary the kernel search radius from one point to another based on the local characteristics of accident data on each road segment as in research conducted by (Ge et al., 2022). Adaptive Kernel Density Estimation can adjust the search radius based on the needs of each road section so that it can reduce estimation bias that occurs due to the spatial influence of events on other road sections. This method can provide an accurate representation of modeling spatial patterns of traffic accidents based on the unique characteristics of each road segment based on a certain bandwidth or search radius.

The results of research on accident vulnerability maps are grouped into three classes based on the number of accidents referring to research conducted by (Siregar et al., 2022), there are low, medium and high. The blackspot map results are grouped into two classes based on the calculation of the Equivalent Accident Number (EAN) combined with the Upper Control Limit (UCL) and Upper Control Limit (BKA) referring to the Departmen Permukiman dan Prasawara Wilayah Regulations (2004), namely not a blackspot and blackspot. The result of accident modeling results then carried out with an accuracy test to determine the extent of the accuracy of the resulting model for future incident data.

These approaches offer solutions to help density modeling of accident vulnerabilty locations and blackspots on a road section. The modeling results can provide a stronger recommendation for optimizing prevention strategies to support more road infrastructure improvements. Through this research, it is hoped that it can become a consideration for the government and the community in Brebes District to increase awareness and safety in traffic.

2. Material and Methods

2.1 Study Area

Brebes District borders with Wanasari District in the West, Tegal City in the East, Jatibarang District in the South, and borders directly on the Java Sea in the North. Brebes District has an area of around 92,23 km2 consisting of 18 villages and 5 sub-districts. The research focuses on the ten sections with the highest accident rates, including Jalan Gajah Mada, Jalan Lingkar Utara, Jalan Pemuda, Jalan Sultan Agung, Jalan Jenderal Sudirman, Jalan Jenderal A. Yani, Jalan Raya Terlangu, Jalan Raya Sigempol, Jalan Bina Desa, and Jalan Sultan of Gunung Jati.

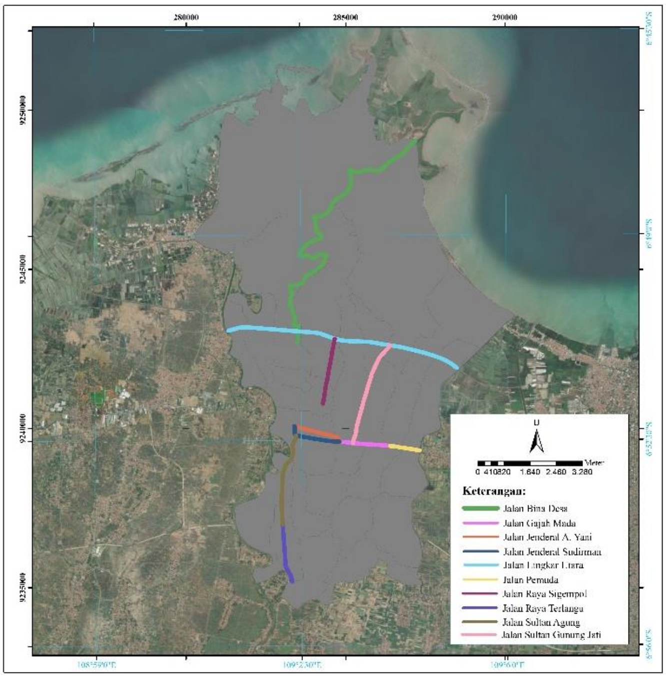


Figure 1. Research Area

2.2 Data

The data used in this research processing includes:

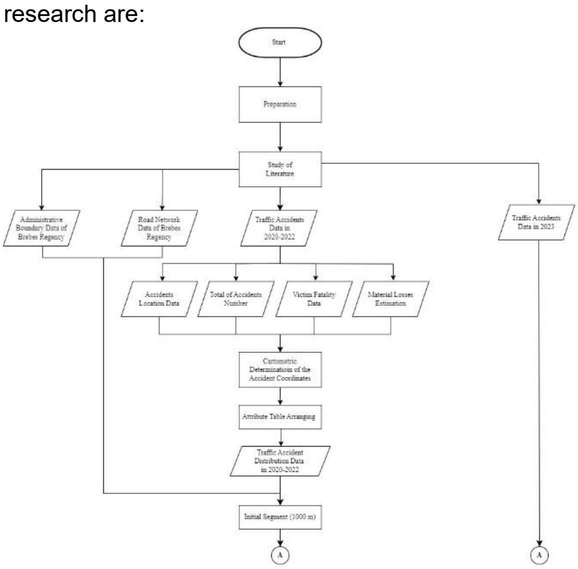
Table 1 Research data

Types of Data	Source
Administration Boundaries Data of Brebes Regency Scale 1:25.000	Dinas PUPR Brebes
Road Network Data of Brebes Regency Scale 1:25.000	Dinas PUPR Brebes
Traffic Accident Data in Brebes District 2020-2022	Satlantas Brebes
Traffic Accident Data in Brebes District 2023*	Satlantas Brebes

* Data is used to test the accuracy of modeling the vulnerability and blackspots of traffic accidents that are formed.

2.3 Research Flow Chart

In general, the processing steps carried out in this research are:



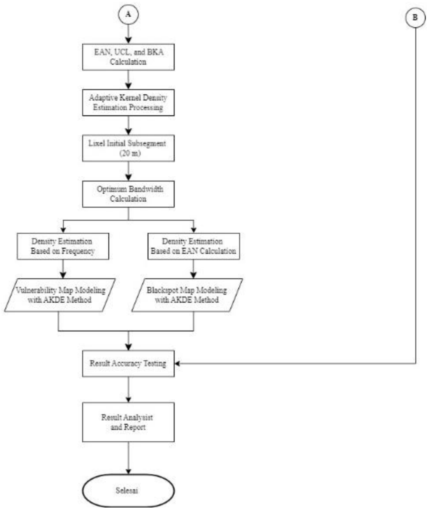


Figure 2. Research Flow Chart

2.4 Traffic Accident

According to Pasal 1 Undang-Undang No. 22 Tahun 2009, a traffic accident is defined as an unexpected and unintentional incident on the road involving a vehicle with or without other road users which results in human casualties and/or property loss. A traffic accident is defined as an unexpected or unplanned accident that occurs on the road or as a result of human error, which results in injury, illness and loss, both to people, goods and the environment (Manganta et al., 2019).

Several factors can cause accidents, such as human factors, vehicle factor, road and environmental factors. Based on information obtained from Satlantas Polres Brebes, types of traffic accidents can be grouped into several categories, namely accidents based on victims, based on vehicle position, based on the number of vehicles involved, based on the time they occurred, and based on the traveler.

2.5 Traffic Accident Vulnerability Locations

An accident Vulnerability location is area where the number of accidents is high with repeated accidents in a relatively similar space and time resulting from a particular cause (Departemen Permukiman dan Prasarana Wilayah, 2004). Areas with high accident rates need to receive more attention so that efforts can be made to decrease the severity ratios that may arise(Risdiyanto, 2014).

The traffic vulnerability weighting method used in this research is classified into three classes, referring to research conducted by (Siregar et al., 2022) :

Table 1 Traffic Accident Vulnerability Classification

Number of Accidents (Incidents/Km/Year)	Number of Accidents (Incidents/Km/3 Years)	Class
0-5	0-15	Low
6-10	16-30	Medium
>10	>30	High

2.6 Traffic Accident Blackspot Locations

Black spot locations are dangerous locations prone to accidents on a map which refers to safety conditions with road limits within a radius of 0 – 500 meters and the time span for determining black spots is accident data for a minimum of two years taking into account the severity of accidents (Kakorlantas Polri Decree No. 43/IX/2016). Determination of black spots can also be done by considering material loss estimates or Property Damage Only (PDO) in order to describe maximum vulnerability.

In determining class, there are several methods used to classify whether a section of road is included in the blackspot category or not, including using the calculation of the Equivalent Accident Number (EAN), Upper Control Limit (UCL), and Upper Control Limit (BKA).

1. *Equivalent Accident Number* (EAN)
   Equivalent Accident Number (EAN) is a number used for weighting accident classes, this number is based on the value of accidents with material damage or loss (Departemen Permukiman dan Prasarana Wilayah, 2004). The weighting of victims with minor injuries and serious injuries is 3, deaths are 12, and estimated material losses are 1.
   $$\mathrm{EAN} = 12\,\mathrm{MD} + 3\mathrm{LB} + 3\mathrm{LR} + 1\mathrm{PDO} \qquad (1)$$
   EAN : Equivalent Accident Number (EAN) value
   MD : Number of dead victims
   LB : Number of seriously injured victims
   L.R : The number of minor injuries victims
   PDO: Number of traffic accidents with material losses
2. *Upper Control Limit* (UCL)
   In the process of determining traffic accident blackspots, a process of calculating quality control statistics is carried out which is used as a control chart or also known as the Upper Control Limit (UCL).
   $$\mathrm{UCL} = \lambda + \psi\sqrt{\left(\frac{\mathrm{m}}{\lambda} + \frac{0.829}{\mathrm{m}} + \left(\frac{1}{2} \times \mathrm{m}\right)\right)} \qquad (2)$$
   UCL : Upper Control Limit Value (UCL)
   λ : Average Equivalent Accident Number (EAN) value
   ψ : Probability factor
   m : Equivalent Accident Number (EAN)
3. Batas Kontrol Atas (BKA)
   Batas kontrol Atas is the maximum value permitted as a blackspot determination parameter which is based on the average value of the Equivalent Accident Number (EAN). This value is determined based on statistical analysis of historical data. The BKA calculation formula is as follows:
   $$\mathrm{BKA} = \mathrm{C} + 3\sqrt{\mathrm{C}} \qquad (3)$$
   BKA : Batas Kontrol Atas (BKA) value
   C : Average value of Equivalent Accident Number (EAN)

Tabel 2 Traffic Accident Blackspot Classification

Nilai EAN	Kelas
< UCL dan BKA	Not a *Blackspot*
>UCL dan BKA	*Blackspot*

2.7 Density Analysis

Density analysis is a technique in Geographic Information Systems (GIS) that is used to determine the quantity of a phenomenon and its distribution throughout the landscape based on parameters measured at each location along with the spatial relationship between the location and the measured quantity (ESRI, 2022).

Several density analysis methods include:

1. Point Density
   Point Density is used to calculate the density of each unit area from point data located in an environment around each cell.
2. Line Density
   Line Density is used to calculate the density of each unit area from line data within a certain radius around each cell.
3. Kernel Density
   Kernel Density is used to calculate the density of each unit area from point or line data using the kernel function to smoothly adjust the surface density for each point or line.

2.8 Adaptive Kernel Density Estimation

The Adaptive Kernel Density Estimation method is a complex development of the Network Kernel Density Estimation method with adaptive bandwidth search. NKDE itself consists of 3 types of methods, namely Simple, Discontinuous, and Continuous. This research focuses on using the continuous method because it is the most optimal for estimating without causing bias on road sections with many intersections. Adaptive Kernel Density Estimation can adjust the search radius based on the needs of each road section so that it can reduce estimation bias that occurs due to the spatial influence of events on other road sections

$$\hat{f}(x) = \sum_{i=1}^{n} \frac{1}{n.h} k\left(\frac{X-X_i}{h}\right) \quad (4)$$

f^ (x) : Adaptive Kernel Density density value Estimate at point X
n : The number of sample points that are a distance from sample points are less than or equal to search radius
h : Bandwidth
k : Kernel Function
X-Xi : Distance between point i and point X

The selection of kernel functions and adaptive bandwidth parameters are two important components in the procedure for implementing kernel density estimation (Mahzabeen, 2019). The kernel function used in this research is the quartic function.

$$k(x) = \begin{cases} \frac{3(1-x^2)}{4} & |x| \le 1 \\ 0 & |x| \ge 1 \end{cases} \quad (5)$$

Bandwidth selection is the main element in the kernel density estimation process using this method. If the Mean Square Error has the smallest value, it can be ascertained that the bandwidth is the optimal bandwidth value. There are two types of methods used to find this value, namely Cross Validation Likelihood and Ronie and Van Lieshouts' Criterion.

$$\text{MSE}(h) = \text{E}\left[\hat{f}(x) - f(x)\right]^2 = \text{Var}((\hat{f}(x)) + \text{Bias}(\hat{f}(x))^2 \quad (6)$$

MSE (h) : Mean Square Error for bandwidth h
f^ (x) : Kernel density value
f (x) : Actual density value

2.10 Model Accurary Testing

The results of the vulnerability modeling will then be validated using traffic accident data obtained from the Brebes Police Traffic Unit for the period January-December 2023. This validation test is needed to compare the modeling results with actual data in the field.

$$\text{Tingkat Kesesuaian} = \frac{a+b}{N} \text{ x } 100\ \% \quad (7)$$

a : Number of accidents in high vulnerability
b : Number of accidents in medium vulnerability
N : Total number of accidents

The accuracy test method that will be used in blackspot modeling is the Crash Predictive Accuracy Index (CPAI) method. This method is used because CPAI is not only able to measure the level of success and test blackspot modeling, but also considers road factors as the main element that plays a role in a traffic accident.

$$\text{CPAI} = \frac{n/N}{l/L} \text{ x } 100\ \% \quad (8)$$

CPAI : Crash Predictive Accuracy Index
n : Number of accidents in the black spot subsegment
N : Total number of traffic accidents
l : Blackspot subsegment length
L : The total length of the road

Result and Discussion

3.1 Traffic Accident Distribution Map

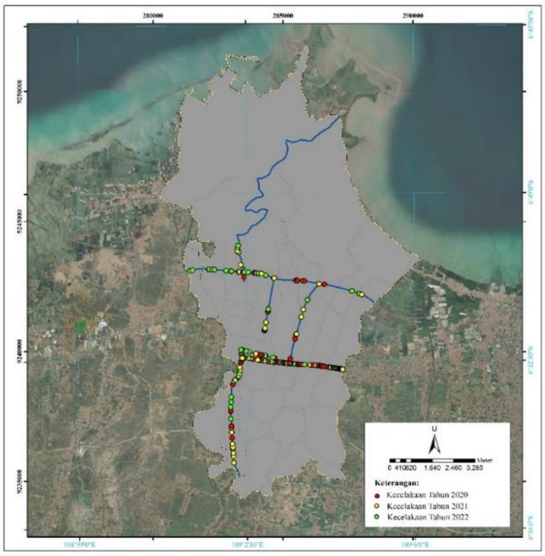
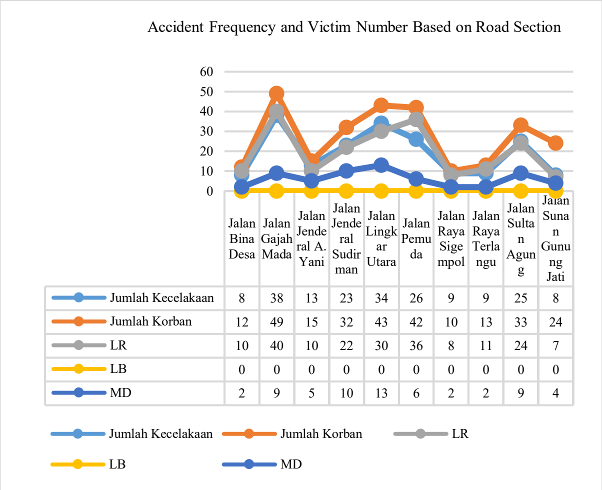


Figure 3. Accident Distribution Map for 2020-2022

According to the results of data processing, traffic accidents that occurred in Brebes District during the last 3 years are show in **Figure 3.** the highest accidents occurred in 2022 with 73 accidents visualized in green, while the lowest accidents occurred in 2020 with 53 accident. Integration between spatial and statistical aspects is able to provide a detailed picture of the distribution characteristics of accidents that occur. Statistical analysis was carried out to determine trends in the frequency and number of accident victims. The injury rate shows the fatality level of victims with minor injuries and serious injuries. The mortality rate shows the level of deaths that occur based on the frequency of accidents.



	Jalan Bina Desa	Jalan Gajah Mada	Jalan Jenderal A. Yani	Jalan Jenderal Sudirman	Jalan Lingkar Utara	Jalan Pemuda	Jalan Raya Sigempol	Jalan Raya Terlangu	Jalan Sultan Agung	Jalan Sunan Gunung Jati
Jumlah Kecelakaan	8	38	13	23	34	26	9	9	25	8
Jumlah Korban	12	49	15	32	43	42	10	13	33	24
LR	10	40	10	22	30	36	8	11	24	7
LB	0	0	0	0	0	0	0	0	0	0
MD	2	9	5	10	13	6	2	2	9	4

Figure 4. Accident Statistics

Data shows that the highest number of accidents occurred on Jalan Gajah Mada with a total of 38 incidents. The highest number of victims also occurred on Jalan Gajah Mada with a total of 49 victims including 40 light injuries, 0 serious injuries and 9 deaths. This road is the main road that connects the Brebes Exit Tol in the east with other regions in Brebes Regency. The large number of crowded centers such as government offices, shopping centers and public facilities creates a high risk of accidents.

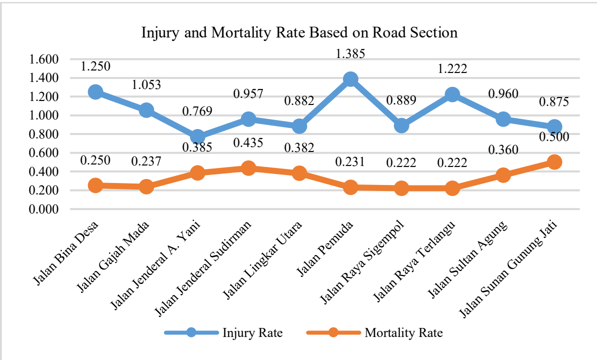


Figure 5. Injury and Mortality Rate Statistics

The calculation results show that the highest injury rate occurred on Jalan Pemuda with a value of 1,385. This road is the main road connecting Brebes Regency and Tegal City. Passing vehicles tend to travel at high speed because the road is wide and straight, causing many victims with minor and serious injuries. The highest mortality rate occurred on Jalan Sunan Gunung Jati with a value of 0.500. The condition of this road is the center of intersections between other roads, causing a buildup of vehicle volume around the BNI Brebes Branch Office.

3.2 Initial Segment Result

Processing begins with the stage of dividing road into segments in 1000 meter intervals on the ten road sections with the highest accidents. Segmentation was processed using GeoWizard extention tools in ArcGIS and formed a total of 31 segments. Then the EAN, UCL, and BKA calculations are carried out as a basis for determining blackspots.

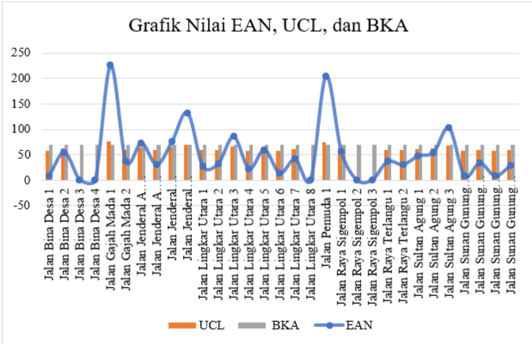


Figure 6. EAN, UCL, and BKA Value Statistics

The total value of the Equivalent Accident Number that occurred on 31 road segments in Brebes District is 1517. The average EAN in the 2020-2022 time period is symbolized by the symbol (λ) and is calculated to be 48,935. A probability factor (ψ) of 2,576 is used to produce a probability of 0,005 so that the confidence value obtained from the UCL calculation is 99,5%. The BKA calculation results simulated from the average EAN value for 2020-2022 on accident data are 69,922. Based on the graph on **Figure 6**, it appears that there are several road segments that have EAN values greater than their UCL and BKA values. These segments are indicated to have a high level of vulnerability and are included in the blackspot category. However, these results cannot yet represent detailed accident modeling. Therefore, the segments formed will be further divided into subsegments every 20 meters in order to produce more accurate accident and blackspot prone modeling using Adaptive Kernel Density Estimation.

3.3 Adaptive Kernel Density Estimation Method Modeling Result

The road segments formed are then divided into subsegments in lixel form with 20 meter intervals in RStudio. Pixel subsegments with 20 meter intervals are used to form discrete nodes to represent more accurate modeling output. The total number of lixels formed is 1352 subsegments. Density estimation using this method is carried out twice, using global bandwidth and local bandwidth. Therefore, it is necessary to calculate the optimum bandwidth sequentially 30 times from a bandwidth of 50-1500 meters using Cross Validation Likelihood calculations and Cronie Van Lieshouts' Criterion.

Table 3. Bandwidth Validation Value

Bandwidth	Cross Validation Likelihood	Cronie Van Lieshouts' Criterion
....	....	....
900	-11,48386499	5,20382E+14
950	-11,53997061	5,89619E+14
1000	-11,59419258	6,62914E+14
1050	-11,64661088	7,40149E+14
1100	-11,69740991	8,22032E+14
....	....	....

Based on the observation results, the Cronie and Van Lieshouts' Criterion method is not suitable for this data because it produces inconsistencies in suggested bandwidth. Therefore, the optimum bandwidth value is selected according to recommendations from the results of the Cross Validation Likelihood calculation. It is known that the error value tends to be stable at -11, this number is then calculated again to produce an average error value, it turns out the result is -11,57275695. Referring to **Table 3**, the closest value to -11,57275695 is -11,59419258 which is owned by bandwidth of 1000 m. Therefore, a bandwidth of 1000 meters is determined as the optimum value.

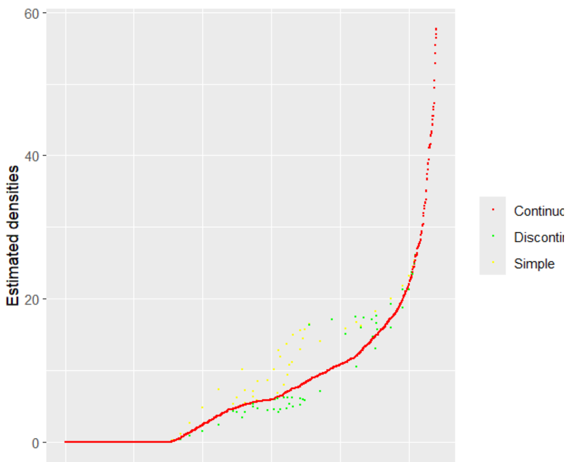


Figure 7. Method Selection Plot

Based on the **Figure 7** above, it is known that the Continuous method produces the best density estimates in describing variations in local characteristics of the data. This method can consider changes in dynamically optimized bandwidth so that it can provide smoother and more accurate estimates that take into account local variations. Therefore, this method is used as the basis for the Adaptive Kernel Density Estimation processing carried out.

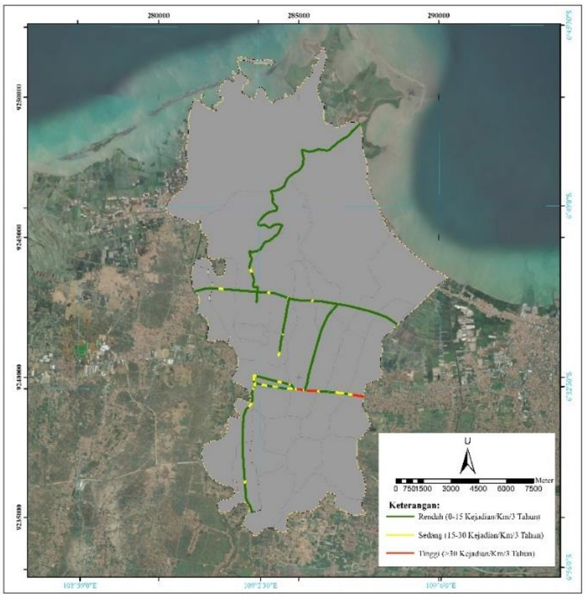


Figure 8. Results of Vulnerability Map Modeling Using Adaptive Kernel Density Estimation Method

The density estimation results based on the number of accidents obtained from Adaptive Kernel Density Estimation processing are used to form a traffic accident vulnerability map. The vulnerability map show in **Figure 8.** The mapping results show that the majority of roads with a high level of vulnerability occur on Jalan Gajah Mada 1 subsegment 191-200, Jalan Gajah Mada 2 subsegment 207-224, and Jalan Pemuda subsegment 795-814.

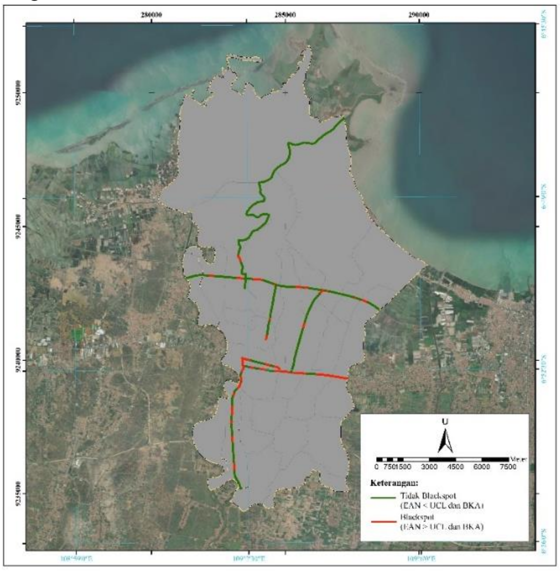


Figure 9. Results of *Blackspot* Map Modeling Using Adaptive Kernel Density Estimation Method

This method identifies that the majority of roads in Brebes District have a low level of vulnerability with a percentage of 85,87% with a total of 1161 sub segments identified, while for medium and high values are 10,58% and 3,55% respectively with the respective numbers 143 and 48 subsegments respectively.

The use of adaptive bandwidth which can adjust to local density makes the mapping results obtained more responsive to complex spatial patterns. Global bandwidth is applied consistently across areas as a fixed parameter in the data space. Local bandwidth is calculated automatically based on the local characteristics of each data so that it is dynamic according to existing local variations.

The blackspot map show in **Figure 9.** The density estimation results based on Equivalent Accident Number (EAN) weighting obtained from Adaptive Kernel Density Estimation processing are used to form a traffic accident blackspot map. The results of Upper Control Limit (UCL) and Batas Kontrol Atas (BKA) calculations on segments obtained at the initial segment division stage are used as determining parameters in blackspot modeling. The mapping results show that the majority of roads with blackspot category levels occur on Jalan Jenderal Sudirman 2 subsegment 340-424, Jalan Jenderal Jalan Jenderal A. Yani subsegment 267-339, Jalan Pemuda subsegment 794-841, as well as several other subsegments.

This method identifies roads in Brebes District which are categorized as traffic accident blackspots with a percentage of 30,62% with a total of 414 identified subsegments, while for the non-blackspot category the value is 69,38% with a total of 984 subsegments. In areas with high density, the local bandwidth will decrease, while in areas with low density the local bandwidth will increase. This combination of calculations between global bandwidth and local bandwidth can produce the actual Equivalent Accident Number (EAN) weighting Adaptive Kernel Density Estimation value.

3.4 Accuracy Testing Result

The results of modeling the vulnerability and blackspots of traffic accidents in Brebes District for 2020-2022 which have been processed using Adaptive Kernel Density Estimation method then tested. The accuracy test was carried out using accident data that occurred in the January-December 2023 range. The aim of this stage is to find out to what extent the modeling results can predict vulnerabilities and blackspots that will occur in the future. Based on the results of cartometric determinations, it is known that in 2023 there will be 97 accidents spread across the research area. **Table 5** shows the results of the vulnerability modeling accuracy test that has been formed.

Table 3 Vulnerability Modeling Accuracy Test Results

High Vulnerabilty	Medium Vulnerabilty	Total Accident	Suitability Level
28	41	97	71,13%

The accuracy test results show that this method modeling vulnerability with the level suitability of 71,13% accuracy. Based on these results, Adaptive Kernel Density Estimation method is not only better at detecting high vulnerability segments but also more efficient in overall classification.

Table 4 show the results of the blackspot modeling accuracy test that has been formed.

Table 4 Blackspot Modeling Accuracy Test Results

Accident on Blackspot	Acci dent Total	Length of Black spot	Length of Roads	CPAI
28	97	10839,133	26935,878	71,73%

The CPAI calculation results show that the Adaptive Kernel Density Estimation method can produce a CPAI index of 71,73%. The shorter the blackspot that can be identified and the more accidents that are identified will provide a higher CPAI value. AKDE identified the blackspot area with a total length of 10839.133 meters, this length shows that AKDE quite inclusive in defining blackspot areas. AKDE offers broader and more sensitive coverage.

4. Conclusion

The distribution pattern of traffic accident density shows that the highest number of incidents occurred in 2022 with a total of 79 incidents. The road section with the highest accident rate occurred on Jalan Gajah Mada with a total of 38 incidents. Based on the results of the processing that has been carried out as a whole, it is known that the Adaptive Kernel Density Estimation method produces a level of model suitability with accuracy 71,13% and the CPAI calculation results show that the Adaptive Kernel Density Estimation method is better in carrying out blackspot modeling because it can produce a CPAI index of 71,73%.

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