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Modeling and Simulation of Vehicle Velocity-Density on Buah Batu Road Using Second-Order Polynomial Regression

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ABSTRACT

Keywords: velocity, density, velocity-density function, second order polynomial regression, lax-wendroff scheme.

The problem of traffic density is complex in the world of land transportation, especially in urban areas, including Bandung City. Buah Batu Road, one of the main roads in Bandung City is 13 meters wide and 1.70 kilometers long, connecting Bandung City and Bandung Regency. This study examines the relationship between vehicle speed and traffic density on Buah Batu Road, Bandung. Using the macroscopic Lighthill-Whitham Richards (LWR) model, Second Order Polynomial Regression, and Lax-Wendroff scheme simulation. This study aims to obtain the speed-density function for traffic. The introduction emphasizes the importance of understanding traffic flow dynamics to reduce congestion, especially in areas with significant vehicle growth. The methodology used is direct observation of the Buah Batu Road section with an observed length of 18 meters, with data collected through cellphone camera recordings at various times. These observation data provide insight into vehicle density and speed under various conditions.

Introduction

The problem of traffic density is complex in the world of land transportation, especially in urban areas, including Bandung City. (Nugroho Julianto, 2010). Congestion generally occurs at road intersections, especially during rush hour, namely in the morning when employees go to work, or children go to school and in the evening when they come home. (Triwibisono & Aurachman, 2020). With rapid population growth, data from 2020 shows that there were 1.2 million two-wheeled vehicles in Bandung City and 536 thousand four-wheeled vehicles (Dewi, Badruzzaman, Fajar, Suhaedi, & Harahap, 2020). The problem of congestion has become a major challenge for the quality of life of citizens, not only disrupting travel delays, but also increasing the risk of traffic accidents, damaging air quality due to vehicle emissions, and disrupting community productivity.

Traffic flow characteristic types are generally categorized into three models, namely Macroscopic, Microscopic, and Mesoscopic (van Wageningen-Kessels, van Lint, Vuik, & Hoogendoorn, 2015). The macroscopic model views traffic as a continuous fluid flow and analyzes variables such as speed, density, and traffic flow. Then, the Microscopic model is a model that observes individual vehicle behavior and interactions between vehicles, which focuses more on analyzing acceleration, deceleration, and distance between vehicles. Then, the Mesoscopic model is a model that combines the Macroscopic and Microscopic approaches (J. Popping, 2013).

Buah Batu Road is 13 meters wide and 1.70 kilometers long, connecting Bandung City and Bandung Regency. It is located near several important locations, such as toll roads, food places, and other entertainment centers. (Duddy Studyana et al., 2020), and make this road frequently passed. With the high volume of existing vehicles, Buah Batu Road also faces a tough challenge in maintaining smooth traffic and avoiding congestion that has the potential to harm mobility on Buah Batu Road. (Fadriani & Pirmansyah, 2022).

Fig. 1. Illustration of Conditions on Buah Batu Road

An illustration of traffic congestion can be seen in Fig. 1. This journal will observe the relationship between speed and traffic flow density. The speed function depends on the speed of the vehicle. Therefore, the second-order polynomial regression function approximates the speed function from the observed data. The speed function is obtained from the relationship between the average velocity of vehicles. (v) and density (ρ)In traffic flow.

This study analyses and simulates a traffic flow model based on the velocity-density function obtained from observation data. The structure of this journal is arranged as follows, Introduction introduces the research topic, Methods discusses the macroscopic model of traffic flow and the application of Second Order Polynomial Regression, Results and Discussion present the results and discussion of the methods used, and finally Conclusion presents the conclusions of this study.

Method

Traffic Flow Model

Traffic flow analysis involves the movement of vehicles in a road network, which involves complex interactions between vehicles, drivers, and road infrastructure. This study uses the Lighthill-Whitham-Richards (LWR) macroscopic model, which is the basis of traffic flow theory. The Lighthill-Whitham-Richards (LWR) model examines important characteristics such as vehicle density, speed, and travel time. This model is based on the continuity equation and assumes a balanced relationship between speed and density. The continuity equation ensures that the number of vehicles in a given area remains constant over time (Wong & Wong, 2002).

The equation form of the Lighthill-Whitham-Richards (LWR) model is presented as follows. (Vikram, Chakroborty, & Mittal, 2013):

$$\frac{\partial \rho}{\partial t} + \frac{\partial q}{\partial x} = 0 \quad (1)$$

By replacing ∂q with $\rho U(\rho)$In this equation, we get (Harry Gunawan, 2014), (Gunawan & Siahaan, 2017):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho U(\rho))}{\partial x} = 0 \quad (2)$$

In equation 2, ρrepresents the vehicle density, indicating how this density changes over time. The variable $t$refers to vehicle travel time, which describes changes in density over some time. The term $\rho U(\rho)$signifies the velocity function dependent on vehicle density, meaning the average velocity of vehicles varies according to traffic density. The variable xIs the positional variable, indicating spatial changes along the road network. In simulating a traffic flow model, it is first necessary to define the velocity function. This paper uses second-order polynomial regression to estimate the velocity function based on observed data.

Polynomial Regression

Polynomial regression is a statistical analysis method used to model the relationship between independent variables. x and dependent variable y using polynomials of degree n (Liu & Deng, 2021). This method involves fitting a polynomial curve to the data, which allows for a more accurate estimation of complex relationships between variables than simple linear regression. The result is a polynomial function that minimizes the error between predicted values and observed data. This paper will use second-order polynomial regression to obtain a velocity function based on observed data. The independent variable used in this function is density, while the dependent variable is velocity.

The following is the general form of the Polynomial Regression equation. (Ostertagová, 2012).:

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3 + \ldots + \beta_n x^n + \epsilon \quad (3)$$

Because this journal will use second-order polynomial regression, the equation used is:

$$= \beta_0 + \beta_1 x + \beta_2 x^2 + \epsilon \quad (4)$$

In equation 4 y is the dependent variable, x is an independent variable, β_0Is an intercept, β_1Is the linear coefficient, β_2 is the quadratic coefficient, and ϵIs the error term. This model captures the non-linear relationship between x and y.

Results and Discussion

In this Journal, data collection was conducted through direct observation on Buah Batu Road, Bandung, West Java, Indonesia. The length of the observed road section was 18 meters. Data were collected from one direction of the road, specifically the road section marked in Fig. 2. This Journal considers 4 motorcycles in the observation which is equivalent to 1 car, and one truck or bus is equivalent to 2 cars.

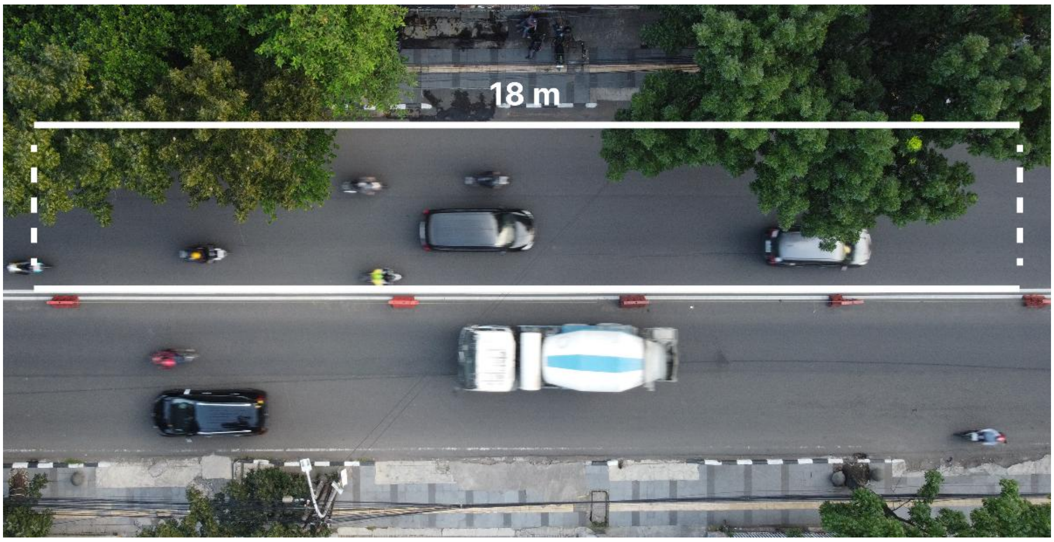

Fig. 2 Location of the Dataset was Taken

Data collection was carried out over several days at different and random times, by recording traffic conditions using a tripod-mounted camera in video form. After obtaining the data, the data was preprocessed by converting the video into numeric data which was then entered into Excel format to facilitate data collection and made into .csv format. Furthermore, Fig. 3 provides a location where the recording camera was positioned for data collection.

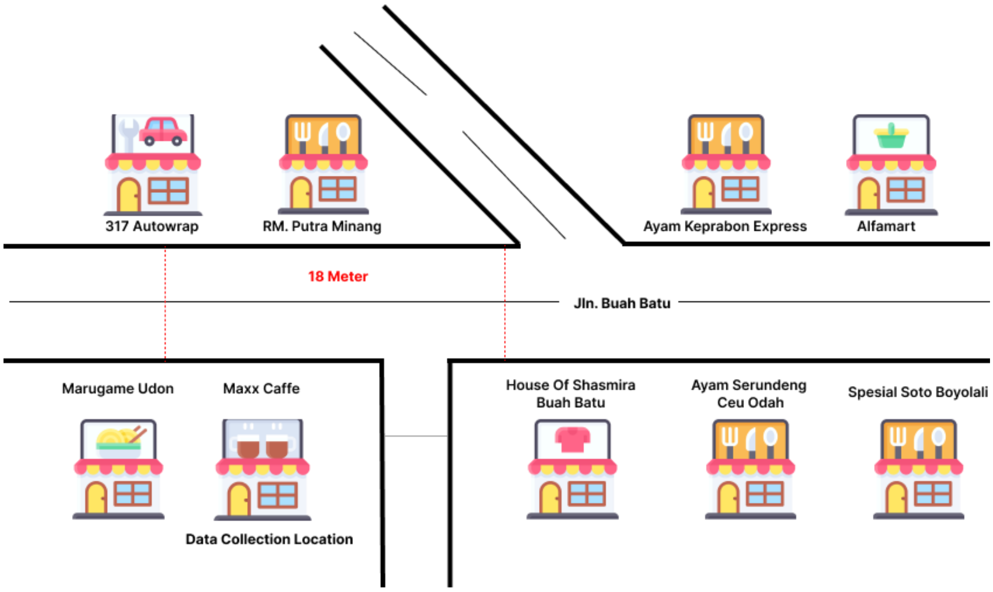

Fig. 3 Plan of the observation site

Approximation of Velocity Function

Table 1
Buah Batu Road Traffic Flow Dataset

No	T-In	T-Out	Δt	Speed	Density
1	00:29	00:39	10	1.80	0.55
2	00:32	00:55	23	0.78	0.41
3	00:33	00:45	12	1.50	0.48
4	00:36	01:00	24	0.75	0.48
5	00:36	00:48	12	1.50	0.48
…	…	…	…	…	…
500	07:47	07:50	3	6.00	0.03

The main purpose of data observation is to obtain the speed function by collecting data on traffic flow density, and vehicle speeds encountered in the observation location. In total, 500 data have been collected. This data set is detailed in Table 1. The next step involves calculating the speed and density functions with the collected data. The calculation equations used are as follows:

$$\rho = \frac{V}{V_{max}}, \quad v = \frac{L}{\Delta t} \quad (5)$$

Where ρIs the density, v is velocity, VIs the volume of vehicles, V_{max}Is the maximum volume that can be accommodated in the domain, L represents the length of the studied road domain, and ΔtIs the travel time. The results of the velocity function using second-order polynomial regression can be seen in Fig. 4.

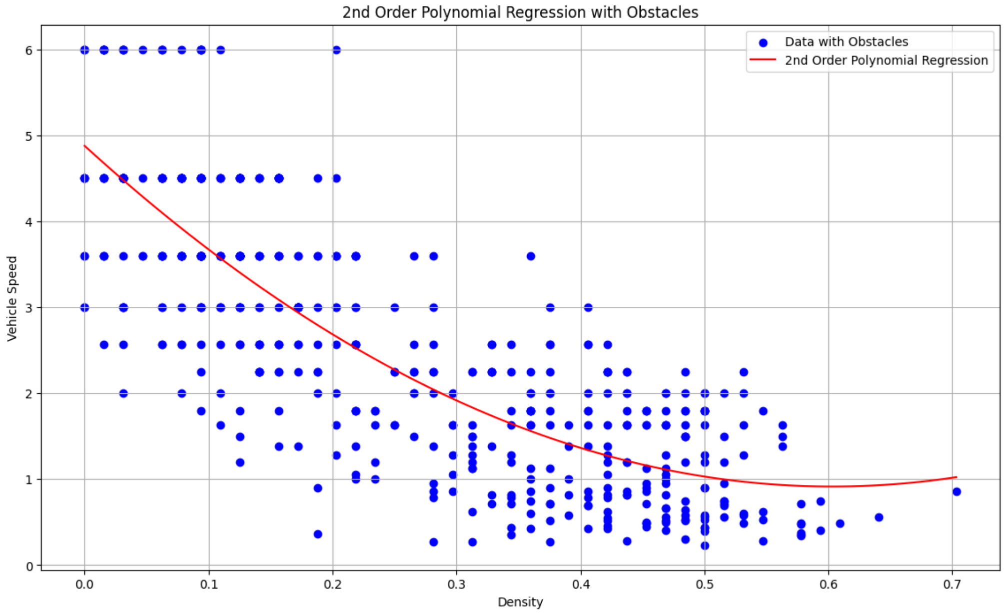

Figure 4 Second Order polynomial Regression Dataset Model Result

Fig. 4., shows a gradual decrease in vehicle speeds as density increases. The red line shows a less pronounced but similar trend, with speeds decreasing significantly at first, then slowing down, and increasing slightly at very high densities. Fig. 4. highlights how density has a significant impact on traffic flow and vehicle speeds. As a result, the speed function obtained by following equation 5 is:

$$v(\rho) = -12.995\rho + 4.819$$

With coefficient ρ negative value of the speed function indicates that increasing density consistently decreases vehicle speed, indicating that vehicles tend to move slower in dense traffic conditions. The intercept of the function represents the initial vehicle speed as density approaches zero, with an estimated maximum speed of about 4.819.

The second-order polynomial regression used in this analysis captures the non-linear relationship between density and vehicle speed, with the regression curve showing a sharper decrease in speed at higher densities. This reflects that as traffic becomes denser, vehicle speeds can significantly reduce. This analysis provides strong evidence that increasing traffic density is directly correlated with decreasing vehicle speeds.

Numerical Simulation

The traffic flow simulation used is the Lax-Wendroff simulation for vehicle density along the Buah Batu road. Initialization is carried out on a road length of 100 units with 101 discrete points. The initial density is set at 0.45. The characteristic speed is calculated based on the previously determined polynomial coefficients for both conditions, and the simulation runs for 300 time steps with a time interval of 0.01 units.

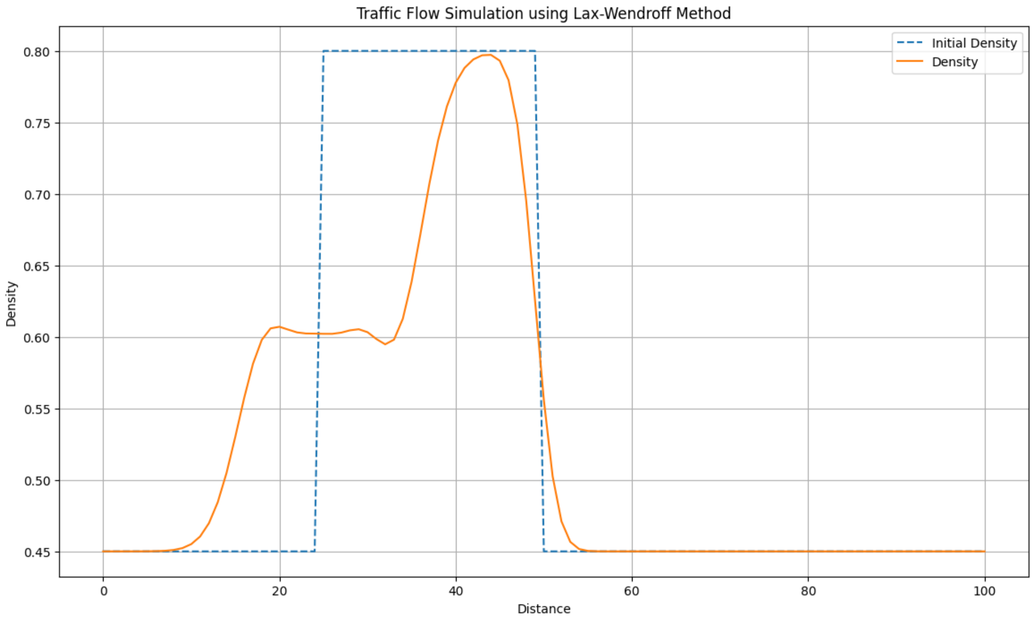

Figure 5 Traffic flow simulation with the Lax-Wendroff scheme after Smoothing

The Lax-Wendroff scheme is a numerical method for solving hyperbolic conservation laws in one-dimensional space, particularly useful in traffic flow modeling. This conservative scheme ensures the conservation of traffic density over time by applying a second-order Taylor series expansion. The resulting equations model the evolution of traffic density. (ρ)Er discrete time intervals, adjusting the density based on the flow rate and the difference between adjacent points. This method effectively handles non-linearity and discontinuity, making it robust to simulate realistic traffic scenarios. (Babbar & Chandrashekar, 2024).

The simulation results are shown in Fig. 5., which illustrates the initial density distribution (blue dashed line) and the final density distribution after simulation (orange line). A Gaussian filter is applied to the simulation results to produce a more precise graph by reducing noise and smoothing the data. From the simulation results, significant fluctuations occur at the initial road length of 40 to around 50, indicating instability of traffic flow.

The results of the simulation analysis show that increasing density consistently causes a decrease in vehicle speed. The velocity function for this condition is $v(\rho) = -12.995\rho + 4.819$. The intercept indicates the initial speed of vehicles when the density is close to zero, with a maximum speed of about 4,819. The negative coefficient proves that increasing density reduces speed, indicating slower movement in high-density traffic. This underlies the use of second-order polynomial regression in capturing the non-linearity between density and velocity.

Conclusion

The conclusion of this study shows that the Second Order Polynomial Regression method with numerical simulation using the Lax-Wendroff scheme is effective in modeling the relationship between vehicle speed (v) with density (ρ)n the traffic flow of Buah Batu Road. The results of the analysis show that vehicle speed decreases with increasing traffic density. The results of the speed function are as follows, $v(\rho) = -12.995\rho + 4.819$. The negative coefficient of the function indicates that increasing density decreases vehicle speed, and reveals that the density distribution shows significant fluctuations when vehicle congestion occurs.

These findings have important implications for traffic planning and management. Implementing new management strategies can help create more stable and efficient traffic flows, improving safety and comfort for road users. Future research can focus on developing more sophisticated models that incorporate various obstacles and dynamic traffic conditions. For example, incorporating real-world traffic data and adaptive traffic signal control systems can improve the accuracy and applicability of the model. Additionally, extending the model to include variations in driver behavior, road conditions, and weather effects can provide a more comprehensive understanding of traffic patterns.

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