p–ISSN: 2723 - 6609 e-ISSN: 2745-5254
Vol. 5, No. 10, October 2024 http://jist.publikasiindonesia.id/

Modeling and Simulation of Vehicle Velocity-Density on Buah Batu Road Using Decision Tree Regression

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ABSTRACT

Keywords: simulation, decision tree regression, velocity-density.

This study aims to explore and simulate the traffic flow model on Buah Batu Road using the velocity-density function generated by the Decision Tree Regression method. The model utilizes a macroscopic approach, specifically the Lightill, Whitham, and Richards (LWR) model, which considers vehicle interactions. Observational data were collected directly from Buah Batu Road and processed to produce a velocity-density function, which shows that vehicle speed decreases as density increases, following a non-linear but step-like pattern. The velocity function generated by the Decision Tree Regression indicates that for low density ($\rho < 0.102$), the average speed is predicted to be around 3.681 to 4.551, while at high density ($\rho > 0.273$), the speed drops to around 1.411 or lower. The simulation was conducted on a 60-meter road segment with a total simulation time of 5 minutes and a grid resolution of 300 points. At the beginning of the simulation, a peak density of 0.70 was recorded in the 15-25 meter segment, which then shifted and decreased to 0.50 in the 30-50 meter segment by the end. The results indicate that vehicle movement reduces density and improves traffic flow. Thus, the Decision Tree Regression method has proven effective in modeling and simulating the velocity-density relationship to understand traffic dynamics on Buah Batu Road.

Introduction

Traffic congestion tends to occur in areas with high activity intensity and extensive land use (Putri & Herison, 2019). Traffic congestion is a common issue in major cities, including Bandung face (Triwibisono & Aurachman, 2020). Bandung is a significant center of economic and social activity in Indonesia. However, rapid economic growth and an increase in the number of vehicles have led to worsening congestion in various parts of the city. Bandung has approximately 2.2 million vehicles, consisting of 1.7 million motorcycles and 500 thousand cars (Hakim & Guntur, 2017). This figure is almost equivalent to the city's population, which reaches 2.4 million people). This phenomenon creates serious city mobility and traffic congestion challenges. One area that frequently experiences congestion is Jalan Buah Batu. Traffic congestion problems tend to occur in areas with high activity intensity and extensive land use (Prayitno & Wasiwitono, 2016).

Buah Batu Road is approximately 1.70 km long and 13 meters wide. Its strategic location connects various areas, including toll roads, shopping centers, industrial zones, and residential areas, making it a primary choice for people to reach frequently visited places. This results in high traffic volumes on Buah Batu Road, leading to obstacles and reduced vehicle speeds (Bestari, Selintung, & Salmon, 2023). However, due to its strategic role, Buah Batu Road also faces significant challenges in ensuring smooth traffic flow and preventing congestion, which can negatively impact Bandung's mobility and economy (Putra, 2017).

To illustrate traffic congestion caused by various obstacles that lead to increased density, refer to Figure 1. In this figure, four motorcycles are considered equivalent to one vehicle, and trucks are shown as the largest obstacles. Vehicles are categorized into two types: large vehicles and small vehicles. Large vehicles include trucks and buses with a length of more than 5 meters and a width of more than 2.5 meters, while small vehicles include passenger cars and motorcycles with a length of less than 5 meters and a width of less than 2.5 meters (Saputri, Nugraha, & Amila, 2014).

Previous research on traffic flow simulation has focused on density and speed but was less intensive and limited in the variables studied (Gunawan, 2014). This study will expand the variables using the Upwind Scheme Simulation and the Decision Tree method based on Mean Squared Error (MSE) to model the relationship between density, speed, volume, and obstacles on Jalan Buah Batu. The results of this simulation will provide insights into traffic congestion and help find effective solutions.

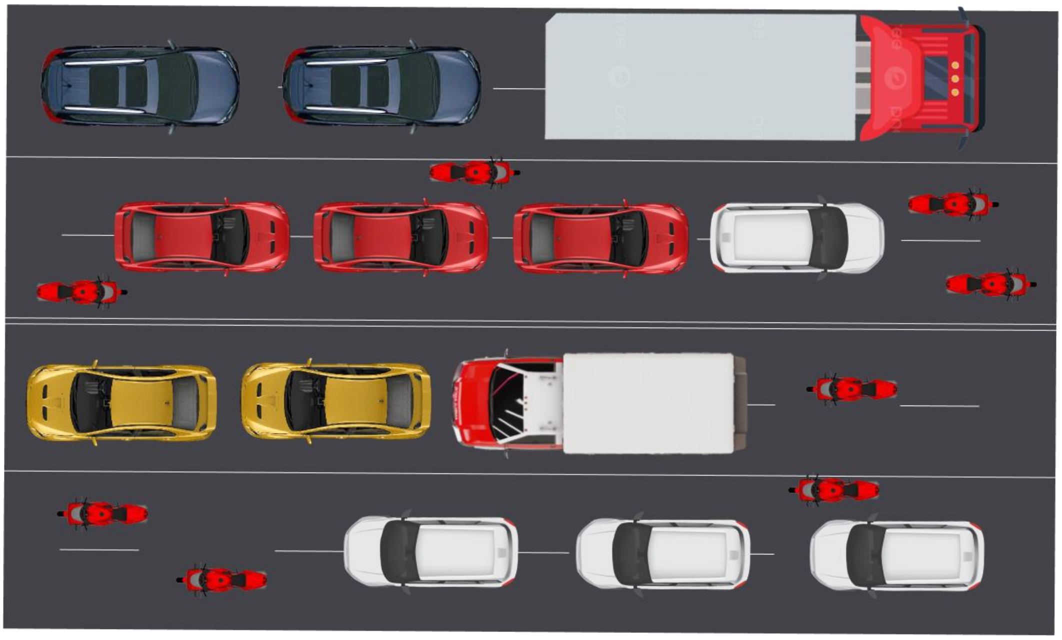

Figure 1

Illustration of the observation area

This journal aims to explore and simulate a traffic flow model by approximating the velocity-density function derived from observational data.

Method

Traffic Flow Model

The macroscopic traffic flow model used in this study is the Lighthill-Whitham-Richards (LWR) model, which is a fundamental model in traffic flow theory. The LWR model is based on the principle of vehicle conservation (Gunawan, 2014), which states that the number of vehicles remains constant within a certain road segment over time. Fundamentally, traffic flow models apply the principle of mass conservation. In the context of traffic, this principle indicates that the flow of vehicles entering and leaving an observation point over a certain period remains stable. This study uses the macroscopic traffic flow model, specifically the Lighthill-Whitham-Richards (LWR) model, which describes traffic dynamics through the conservation equation.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0 \tag{1}$$

$$v(0) = \rho_{max} \quad \text{and} \quad v(\rho_{max}) = (0) \tag{3}$$

By incorporating the relationship between velocity and density into the conservation equation, we obtain the transport equation:

$$\frac{\partial \rho}{\partial \mathrm{t}} + v(\rho)\frac{\partial \rho}{\partial \mathrm{x}} = 0 \tag{4}$$

In this study, the velocity function v(ρ) is determined using the decision tree regression method. This approach is chosen to account for the relationship between velocity and density. This research aims to model and accurately investigate traffic flow models using regression analysis.

Mean Squared Error (MSE) dalam Decision Tree Regresion

The system's performance is evaluated using the Mean Squared Error (MSE) calculation (Aldi, Jondri, & Aditsania, 2018), where the best model is the one with the lowest MSE value (Kushwah et al., 2022). Mean Squared Error (MSE) is the squared difference average between the predicted and actual values. In the context of regression using a decision tree, MSE is used to split the data based on features, in this case, density (ρ), to predict the target, which is speed. The MSE formula can be written as follows:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left((y_i - {y'}_i\right)^2 \tag{5}$$

Explanation:

n is the number of samples in the node
y_i is the actual value of the vehicle's speed
${y'}_i$ is the predicted value based on the tree split

Upwind Scheme

The Upwind Scheme is a first-order finite difference method used to approximate solutions for the vehicle density conservation equation. This approach is well-suited for hyperbolic partial differential equations commonly found in traffic flow models. It is noted for its simplicity in implementation and computational efficiency, making it a practical choice for numerical simulations.

Consider a one-dimensional domain [0, L], where L represents the length of the domain, which is discretized into N points. The following notation is introduced:

$$\Delta x = \frac{L}{N}, \Delta x_i = i \times \ \Delta x \ \ i \in \{0, 1, \dots, N\}$$

$$t^n = n \times \Delta t, n \ \in \{0, 1, \dots\}$$

Where Δx and Δt represent the spatial and temporal steps, respectively, the Upwind Scheme can be formulated as follows:

$$\rho_i^{n+1} = \rho_i^n - \frac{\Delta t}{\Delta x}(\alpha_+(\rho_i^n - \rho_{i-1}^n) + \alpha_-(\rho_{i+1}^n - \rho_i^n) \qquad (6)$$

Where ρ_i^n is the traffic density at position i dan time $n. \alpha += \max(u(\rho_i^n), 0)$ and $a -= \min(u(\rho_i^n), 0)$ are the positive and negative components of the velocity function, which ensure that the method accounts for the flow direction. Finally, the procedure for solving the transport equation using the Upwind Scheme is detailed in Algorithm 1:

Algorithm 1 : Prosedure For Computing The Upwind Scheme	
1	Procedure Upwind FD(F (X), N , L, T , ΔT)
2	Start
3	Define $\Delta X = L/N$
4	Initialize Density: Set Initial Traffic Density $P(X, 0)$
5	Calculate Velocity
6	Determine The Density At The Next Time Step Using (6)
7	Update Traffic Density
8	Repeat Steps 6-7 Until Final Time T Is Reached
9	End Prosedure

Dataset

In this study, the dataset was created on Buah Batu Road, with an observation length of 18 meters in one direction. Data was collected over several days at different and random times by recording traffic conditions in video format. After the data was obtained, preprocessing was carried out by converting the video into numerical data. This data was then entered into an Excel format for easier documentation and converted into a .csv format. A sample of the dataset obtained can be seen in Table 1.

Table 1
Sample Dataset of Buah Batu Road

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 primary objective of this data collection is to derive a speed function by gathering information on traffic density and vehicle speed at the observation site. A total of 500 data points were collected, detailed in Table 1. The next step involves calculating the collected data's speed and density functions. The equations used for these calculations are as follows:

$$\rho = \frac{V}{V_{max}}, \quad v = \frac{L}{\Delta t} \tag{6}$$

Results and Discussion

The research began with a survey and direct data collection on Buah Batu Road, observing vehicle movements over an 18-meter stretch in one direction. Focusing on one direction, this study provides a detailed analysis of vehicle dynamics on that road segment. For research purposes, four motorcycles were considered equivalent to one car. Data was collected over several days at different and random times, using a camera mounted on a tripod to record traffic conditions in video format. Once the data was collected, it was preprocessed by converting the video into numerical data, stored in Excel format for easier management, and converted into a .csv format. The next stage involved creating a decision tree model using MSE based on the formula and data obtained. After the model was created, simulations were conducted to test the model's hypothesis, evaluate alternative solutions, and visualize the results. The final step was analyzing the simulation results to understand how these variables influence each other.

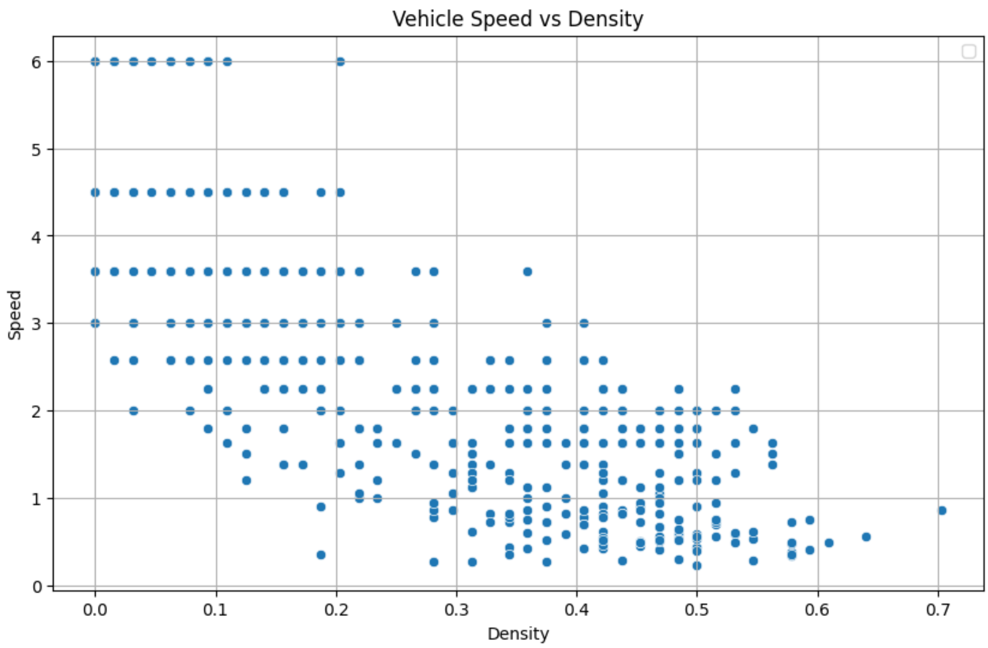

Figure 2
Buah Batu Road dataset graph: Speed vs Density

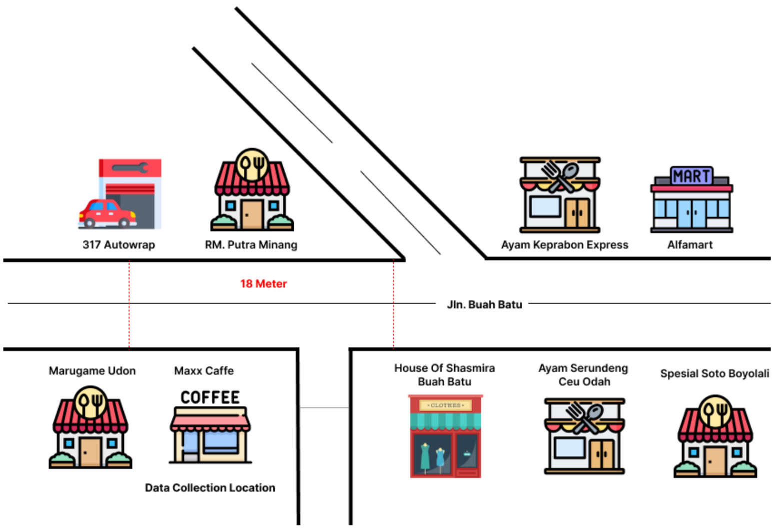

Figure 3
Layout of the observation area

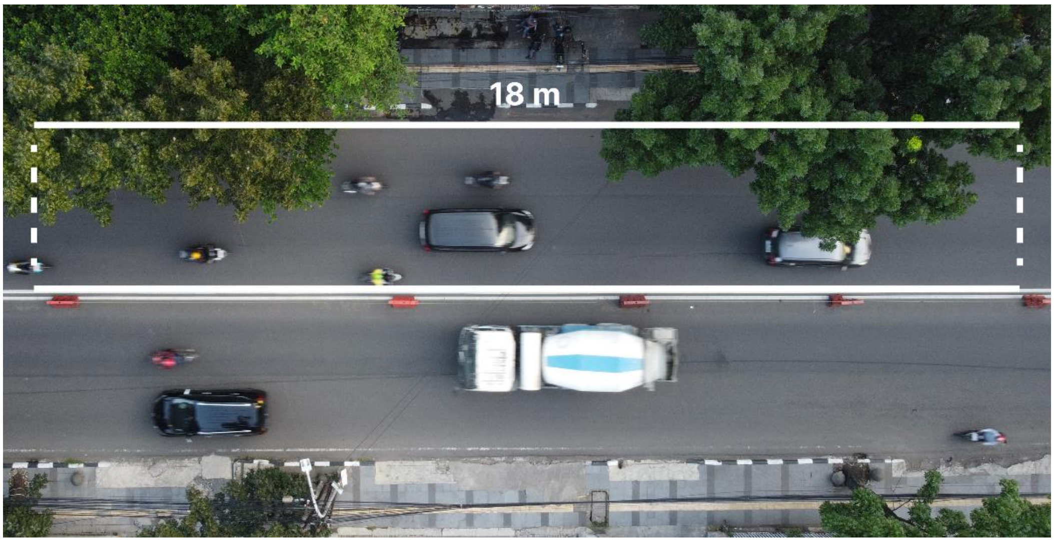

Figure 4
Actual conditions in the observation area

Figure 2 shows the results of the dataset that has been obtained, while Figure 3 presents the layout and actual conditions of the observed area. The purpose of this observational data collection is to determine the velocity function. This is achieved by gathering detailed information, including the average velocity and vehicle density passing through the observation area. This function is represented in equations (6) and (7). The velocity function results can be obtained using a Decision Tree based on Mean Squared Error (MSE), as shown in Figure 5. The velocity function in the figure is derived from the Decision Tree.

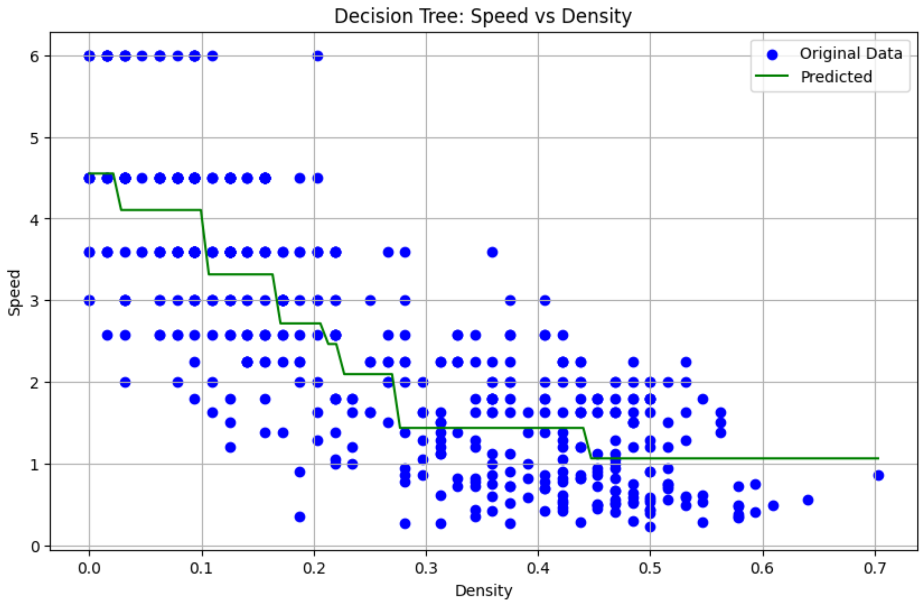

Figure 4
Decision tree visualization: speed vs density

The parameters in this graph indicate that traffic velocity tends to decrease as vehicle density increases. However, in this Decision Tree model, the decrease is not entirely linear but stepwise. The negative slope of the prediction line suggests an inverse relationship between velocity and density. This graph provides a fairly accurate representation of the observational data, and these results can be used as a basis for further numerical simulations, where the velocity function generated from this model will be applied.

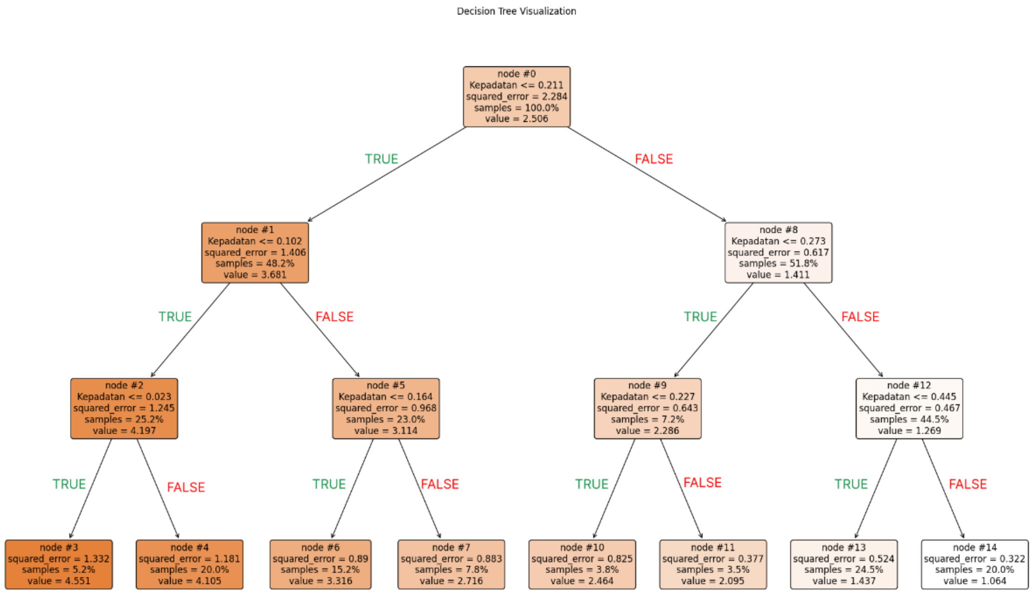

Figure 5
Visualization of decision tree model results

The decision tree visualized in the figure illustrates how vehicle velocity is influenced by traffic density. The data is split at each node based on a specific density value, and the average velocity is predicted for each density interval. For example, if the density is lower than 0.102, the average velocity tends to be higher, reaching around 3.681 or even 4.551 if the density is very low. Conversely, as the density increases to more than 0.273, the average velocity drops to around 1.411 or even lower to 1.064 if the density increases. This decision tree represents a nonlinear relationship between density and velocity, where an increase in density generally results in a decrease in vehicle velocity. The model simplifies velocity predictions based on density intervals, providing insights into the impact of traffic density on velocity effectively.

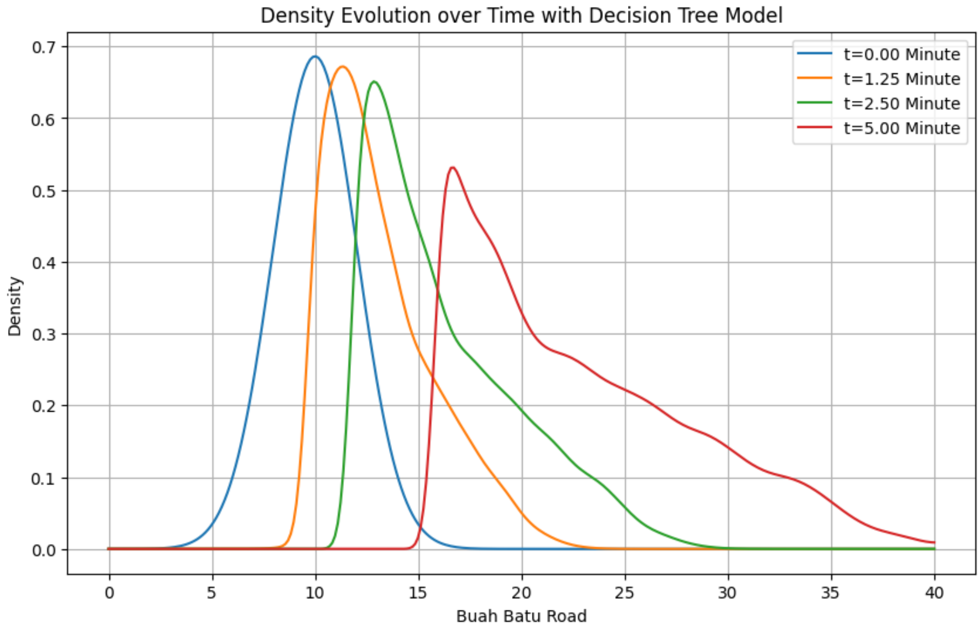

Figure 6
Traffic flow simulation with the upwind scheme

At the initial stage of the simulation (t = 0.00 minutes), conducted along a 60-meter road (L) with a spatial grid of 300 points (nx), the highest vehicle density was recorded in the road segment between 15 and 25 meters, with a peak density reaching approximately 0.70. With a total simulation time set to 5 minutes and time parameters $\Delta t = 0.001$ and $\Delta x = L/nx = 0.2$, this simulation shows a significant accumulation of vehicles in that segment, reflecting the onset of heavy congestion. At this point, vehicles appear stationary or moving very slowly, resulting in a high-density concentration within a relatively narrow area. This initial condition illustrates a situation where traffic flow is significantly obstructed, likely due to road narrowing or other bottlenecks.

As time progresses, the simulation shows that at t = 1.25 minutes, the peak density shifts to the right, around 20 to 30 meters from the starting point, indicating that vehicles are beginning to move forward, although congestion persists in that road segment. By t = 2.50 minutes, the density continues to shift further to the right, reaching around 25 to 35 meters, with a slight decrease in maximum density to 0.60. This suggests that traffic flow is starting to smooth out, and vehicles are spreading out along the road. At the end of the simulation (t = 5.00 minutes), the peak density has shifted to the segment between 30 and 50 meters, and the maximum density has dropped significantly to around 0.50, indicating that congestion has been greatly reduced. With the parameters used, this simulation clearly illustrates how vehicle density changes and decreases over time, reflecting increasingly smoother vehicle movement and significantly reducing congestion on Buah Batu Road.

Conclusion

The conclusion of this study indicates that the Decision Tree Regression method effectively models the relationship between vehicle velocity and traffic density (ρ) on Buah Batu Road. The velocity function generated by this decision tree shows that vehicle velocity decreases as density increases, with the decrease being non-linear but stepwise. This model predicts average velocity based on density intervals, with higher velocity predictions, around 3.681 to 4.551, for low density ($\rho < 0.102$) and a decrease in velocity to around 1.411 or lower at high density ($\rho > 0.273$). The simulation also demonstrated the shift and reduction in vehicle density over time, indicating improved traffic flow as time progresses.

Although this model is simple and effective in understanding traffic dynamics on Buah Batu Road, further research is needed to explore non-linear models or more complex machine learning techniques to capture more intricate traffic dynamics. Additionally, integrating real-time traffic data and adaptive signal control systems is recommended to enhance the accuracy and applicability of this model. Expanding the model to consider variations in driver behavior, road conditions, and weather factors could also provide deeper insights into traffic patterns in busy urban areas.

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