

Shock Wave Analysis at Signalized Intersections (Semplak Intersection)

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ABSTRACT

Traffic congestion in big cities, including Bogor, has increased drastically, with data showing that average travel time has increased by 30% in the last decade. This condition emphasizes the importance of efficient management of signalized intersections to improve mobility and reduce the negative impacts of congestion, such as greenhouse gas emissions and fuel consumption. Based on data from the BPS of West Java Province, the number of vehicles in Bogor Regency/City consists of 184,107 passenger cars, 973 buses, 48,429 trucks, and 1,433,350 motorcycles. If the density increases from zero, then the speed will decrease while the traffic flow will increase. If the density continues to increase, then a condition will be reached where the increase in density will not increase the traffic flow, but instead will decrease the traffic flow. The maximum point of the traffic flow is expressed as the flow capacity. The assumption used in the shock wave at this traffic light intersection is that the passing traffic is relatively low with a constant flow. If the capacity of the intersection arm is greater than the incoming traffic flow, then no vehicles will be held up when the green light is on. Therefore, at a certain distance before and after the traffic light there is a free-flow condition. Based on the results of the discussion of the Shock Wave Analysis study at Signalized Intersections (Semplak Intersection, Bogor City), the conclusions obtained are: 1) According to the results of the analysis obtained from the mathematical relationship between volume, speed and density, obtained from the coefficient of determination (R^2) value which is 0.2973, 2) From the results of the mathematical relationship taken between the Volume and Density of the Greenshield model to analyze the queue length using the shock wave value, the maximum volume (VM) is 1288.843 smp/hour, the maximum density (DM) is 53.2091 smp/km and the current condition is taken $VA = 802.12$ smp/hour which experiences a delay of 175 seconds, the queue length (QM) is 738.67 meters and the normalization time required is 101.024 seconds higher than the duration of the green light which is 70 seconds.

Keywords: BPS, density, duration, shock wave.

INTRODUCTION

Traffic congestion in big cities, including Bogor, has increased drastically, with data showing that average travel time has increased by 30% in the last decade. This condition emphasizes the importance of efficient management of signalized intersections to improve mobility and reduce the negative impacts of congestion, such as greenhouse gas emissions and fuel consumption. Based on data from the BPS of West Java Province [1], the number of vehicles in Bogor Regency/City consists of 184,107 passenger cars, 973 buses, 48,429 trucks, and 1,433,350 motorcycles. With the large number of vehicles, Bogor City has become one of the cities with moderate to high levels of congestion. This congestion is also supported by other road network system problems, namely queues that occur due to traffic lights. One of the main problems in managing signalized intersections is the inability of the existing system to adapt to dynamic fluctuations in traffic volume. Through this research, it is hoped that it can provide new contributions to the development of science in the field of traffic management. This study will identify factors that contribute to shock waves while developing a traffic control model that is adaptive and responsive to changes in traffic conditions. The main objective of this study is to analyze and develop effective traffic control strategies to overcome shock waves at signalized intersections. Theoretically and practically, Based on [2] it is explained that conceptual and comprehensive road management needs to view roads as a unified road network system that binds and connects activity centers. In each road network system,

roads are grouped according to function, status, and road class, the existence of good and well-maintained roads greatly influences the progress of a region.

An intersection is a meeting of road sections that functions to change traffic flow. In general, the capacity of an intersection can be controlled by controlling the volume of traffic in the network system. An intersection is a public area that combines two roads or intersects that have four approach arms. Traffic lights include all traffic control devices that use electricity, except flashing lights, signs, and road markings [3]-[5]. These lights function to direct or warn motor vehicle drivers, cyclists, and pedestrians. The installation of traffic lights usually has one or more of the following objectives:

1. Prevent congestion at intersections by regulating the flow of intersecting traffic, so that a certain capacity can be maintained, even during rush hour. Administrative aspects
2. Provide an opportunity for vehicles and/or pedestrians from small roads to cross the main road.
3. Reduce the number of traffic accidents caused by collisions between vehicles from opposite directions.

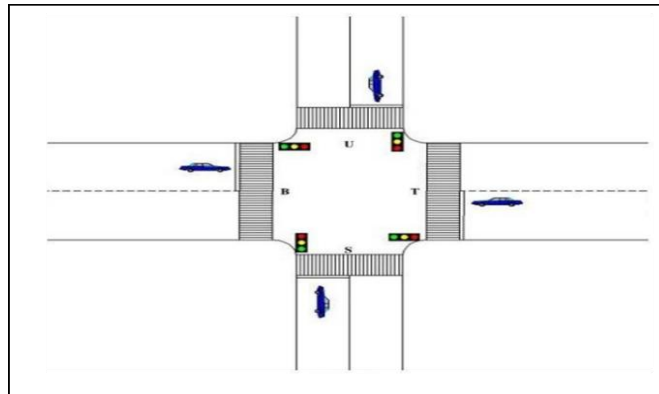


Figure 1. Signalized 4-way intersection [3]

The use of three-color traffic lights (green, yellow, red) is very important to regulate the movement of conflicting vehicles in time. These lights are needed at intersections that often meet or have major conflicts. In addition, traffic lights can also separate turning vehicles from straight vehicles, as well as regulate pedestrians who want to cross so that there is no conflict.

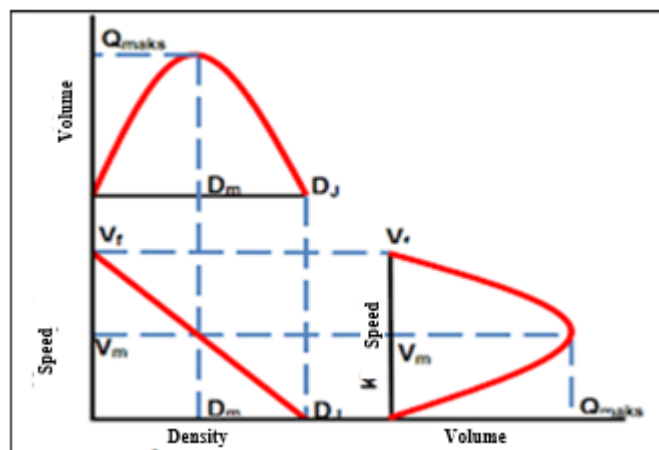


Figure 2. Mathematical relationship between volume, speed, and density [3]

If the density increases from zero, then the speed will decrease while the traffic flow will increase. If the density continues to increase, then a condition will be reached where the increase in density will not increase the traffic flow, but instead will decrease the traffic flow. The maximum point of the traffic flow is expressed as the flow capacity. The assumption used in the shock wave at this

traffic light intersection is that the passing traffic is relatively low with a constant flow. If the capacity of the intersection arm is greater than the incoming traffic flow, then no vehicles will be held up when the green light is on. Therefore, at a certain distance before and after the traffic light there is a free-flow condition. However, at a certain distance before the traffic light while the red light is on, there will be a discontinuity in the traffic flow, namely when the incoming vehicle joins the stopped queuing vehicle and when the vehicle can move again when the green light is on. The Greenshield Model [5] formulates that the mathematical relationship between speed-density is assumed to be linear, as stated by the equation:

$$S = S_{ff} - S_{ff}/D_j \cdot D$$

Shock waves in traffic flow theory describe the propagation of sudden changes in traffic conditions, such as transitions between free-flow and congested states. Using the Greenshields method, shock waves can be analyzed through the fundamental relationship between speed, density, and flow. The Greenshields model assumes a linear relationship between speed and density [6]-[9].

Shock waves occur when there is a discontinuity between two traffic states, such as when vehicles encounter a bottleneck or sudden reduction in capacity. Suppose upstream traffic is characterized by density (k_1) and flow (q_1), while downstream traffic has density (k_2) and flow (q_2). The speed of the shock wave, denoted as (w), is calculated using the conservation of vehicles principle:

$$w = \frac{q_2 - q_1}{k_2 - k_1}$$

This equation represents the speed at which the boundary between the two traffic states moves along the roadway. If (w) is negative, the shock wave travels upstream, which is typical in congestion where vehicles slow down due to a bottleneck. This backward-moving wave explains why drivers experience sudden deceleration even before reaching the actual cause of congestion [10]-[12]. Conversely, if (w) is positive, the wave moves downstream, often occurring when congestion dissipates and traffic returns to normal conditions. Within the Greenshields framework, because flow is a quadratic function of density, differences between two points on the flow-density curve determine the shock wave speed. The linear speed-density assumption simplifies analytical calculations, making it useful for estimating congestion propagation. Thus, the Greenshields model provides a fundamental and practical approach to understanding shock wave dynamics in traffic engineering [13]-[14].

The intersection condition indicates a high level of traffic interaction, particularly during peak hours, where vehicle volumes from multiple approaches converge and create operational conflicts. The junction likely experiences reduced speeds, longer queues, and intermittent stopping due to signal control or competing movements. Traffic flow becomes unstable when demand approaches or exceeds the intersection capacity, resulting in delays and potential spillback to upstream segments [15], [16].

At the junction, merging, crossing, and turning movements increase the number of conflict points, which can reduce efficiency and safety. If there is a short downstream segment or weaving area, vehicles may change lanes abruptly, intensifying turbulence in the traffic stream [17]. Under such circumstances, flow transitions from stable to congested conditions, and shock waves may propagate upstream. Overall, the intersection operates under moderate to heavy demand, with traffic flow characterized by reduced speeds, fluctuating densities, and a higher probability of queue formation during peak periods [18], [19].

RESEARCH METHODS

The research location was carried out at Simpang Semplak Yasmin, which is located in the West Cilendek Area, West Bogor District, Bogor City with latitude coordinates: -6.552027 and longitude: 106.761436. The implementation time of this research starts from September 2024 to April 2025.

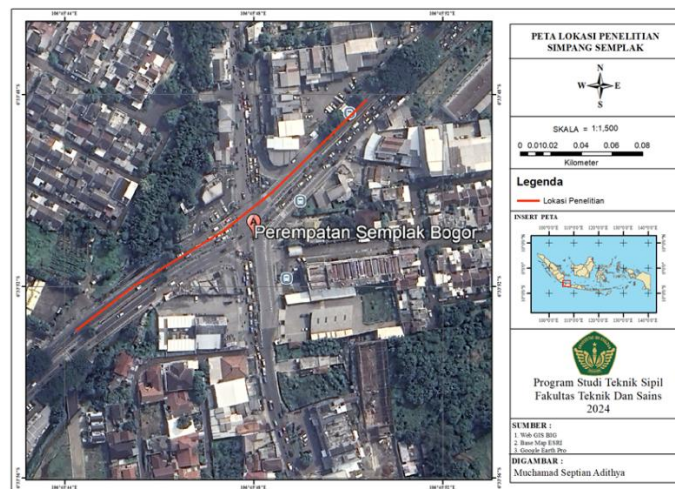


Figure 3. Map of research location

The research flow diagram can be seen in Figure 4 below.

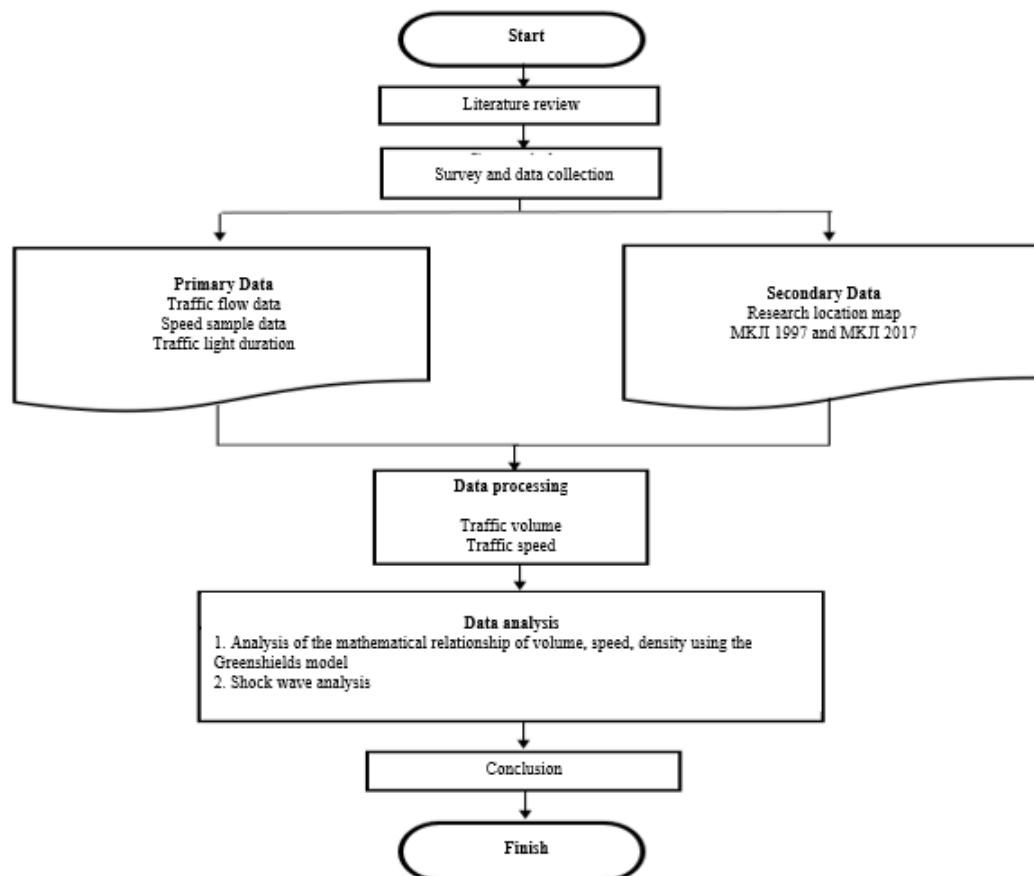


Figure 4. Research flowchart

First, in starting the research, all the needs for field surveys and all kinds of supporting research are prepared, then conducting observations and collecting data related to research in journals and literature books to help analyze data and provide a comprehensive understanding of the topic of shock waves. Data collection, this stage involves two data, namely primary data and secondary data. Primary data: Traffic flow data (volume), speed data, traffic light duration data. Secondary data,

namely [2]. After data collection is complete, the next step is to analyze this data including the number of vehicles passing, vehicle speed, and traffic light time ratio. After the data is collected, the first step is to calculate the total number of vehicles from the survey results conducted in the morning, afternoon, and evening. From the total volume of vehicles, we can calculate the speed of each vehicle. Furthermore, from the speed obtained, we can calculate the density of vehicles. With all this data, we can calculate the Emp of vehicles and continue the shock wave analysis and linear regression analysis. The results of this regression analysis will produce a graph showing the relationship between speed, volume, and vehicle density. Finally, we will also perform a shock wave analysis to create a shock wave diagram.

RESULTS AND DISCUSSION

From the survey results, it can be seen that the maximum volume on Monday occurs in the morning observation from 06:00 to 08:00, at noon from 11:00 to 13:00, and in the afternoon from 16:00 to 18:00. The graph of vehicle volume can be shown in Figure 5 below.

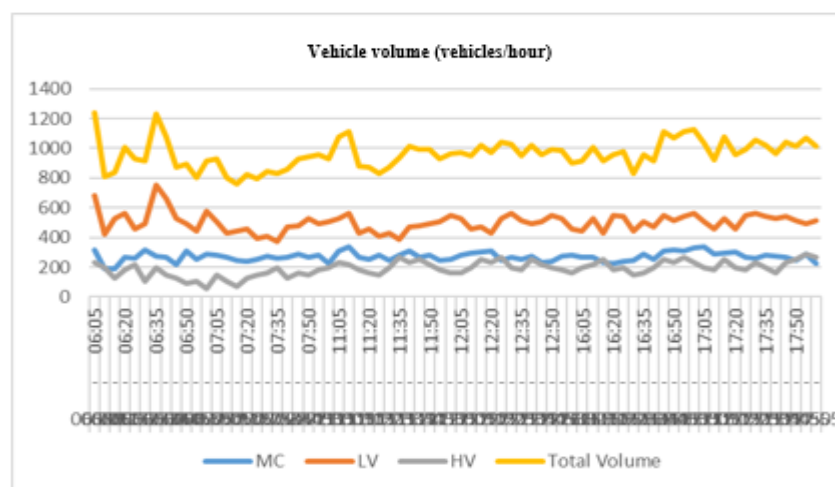


Figure 5. Vehicle volume graph

From the survey results, vehicle travel time data was obtained along the observed road section, for the analysis of traffic flow characteristics, the vehicle speed used was the average space speed (space mean speed), therefore the space speed of each type of vehicle can be searched for the average vehicle space speed (Us). For more details, see Figure 6.

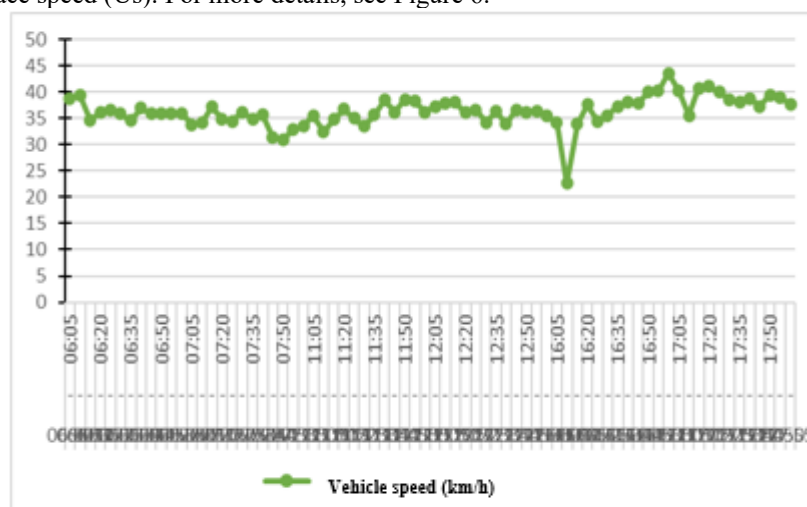


Figure 6. Vehicle speed graph

The results of the speed-density relationship study show that when the density approaches zero, the free flow speed (U_s) is 48.444 km/h, and when the density reaches saturation point or congestion density (D_j) which is 106.41 smp/km, the speed value becomes zero, because it is not possible for vehicles to move again. The results of the speed-density analysis are shown in Figure 7.

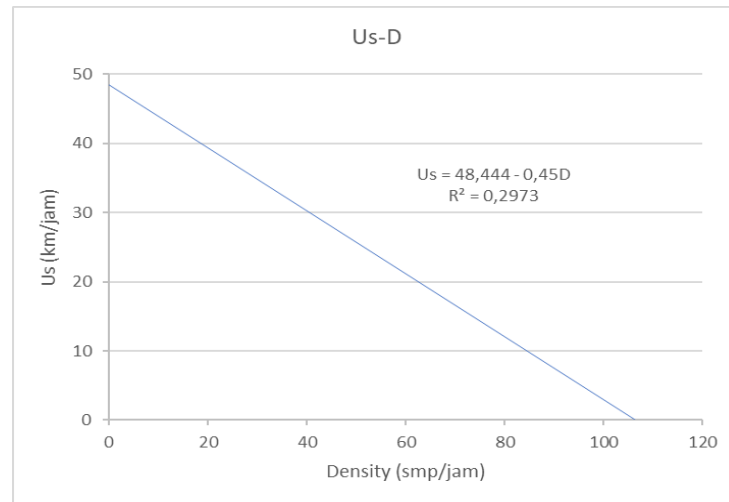


Figure 7. Speed-density relationship

The results of the study of the volume-density relationship, in conditions where the density approaches zero, the traffic volume also approaches zero, assuming that there are no moving vehicles, if the density increases from zero, the volume also increases. At a density when the maximum volume is 53.2 pcu/km, a point will be reached where increasing density will cause the volume to decrease. The results of the speed-density analysis are shown in Figure 8.

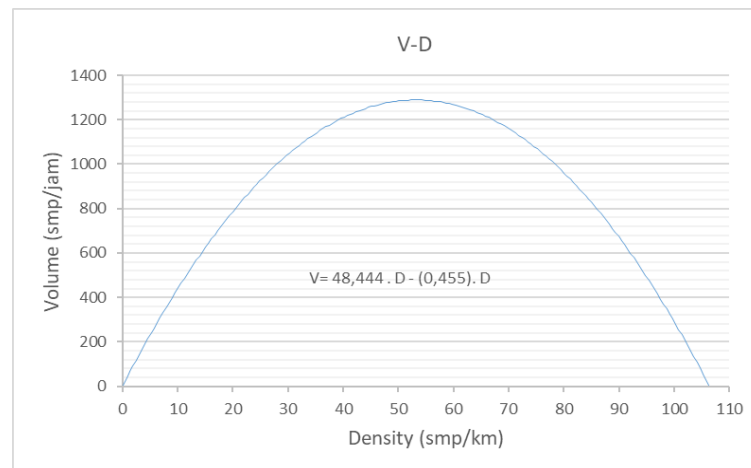


Figure 8. Volume-density relationship

The results of the Greenshield model volume-velocity relationship study, when the maximum volume (V_m) is reached, which is 1288.84 smp/hour, here the speed at maximum volume shows a value of 24.22 km/hour. The results of the speed-density analysis are shown in Figure 9.

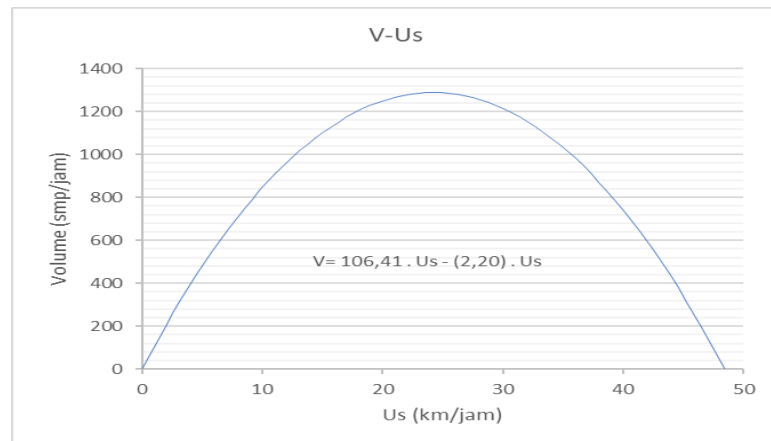


Figure 9. Volume-speed relationship

- a. From the graph results above obtained from the table appendix IV So, the B value obtained from the graph above is 0.455, while the A value from the graph above is 48.44, then the resulting Sff value = 48.44 km / h and Dj = 48.44 / 0.455 = 106.41 smp / km. With the resulting b value = 1 / 0.455 = 2.197

By using the Sff and Dj values, the mathematical relationship between parameters can be determined as follows:

Speed - density relationship: $S = 48.44 - 0.455D$

Volume - Density Relationship: $V = 48.44D - 0.455D^2$

Volume - speed relationship: $V = 106.41S - 2.1972$

- b. Then the maximum volume can be calculated using the equation

$V = 48.44D - 0.455D^2$ and $V = 106.41S - 2.1972$

$\partial V / \partial D = 0$ Obtained $D_m = 106.41 / 2 = 53.20$ smp/km

$\partial V / \partial S = 0$ Obtained $S_m = 48.44 / 2 = 24.22$ km/hour

- c. By entering the value of $D_m = 53.20$ smp/km into the equation $V = 48.44D - 0.455D^2$ or the value of $S_m = 24.22$ km/hour into the equation $V = 106.41S - 2.1972$, the value of $V_m = D_m \times S_m = 0$ will be obtained. Obtained $V_m = 53.20 \times 24.22 = 1.288$ smp/hour. It can be concluded that the maximum volume occurs at a density of $D = 53.20$ smp/km moving at a speed of $S = 24.22$ km/hour.

Shock waves at intersections with traffic lights can be analyzed if the mathematical relationship between the flow density for the intersection arms is known and the traffic flow conditions have been found. Here is the volume-density curve.

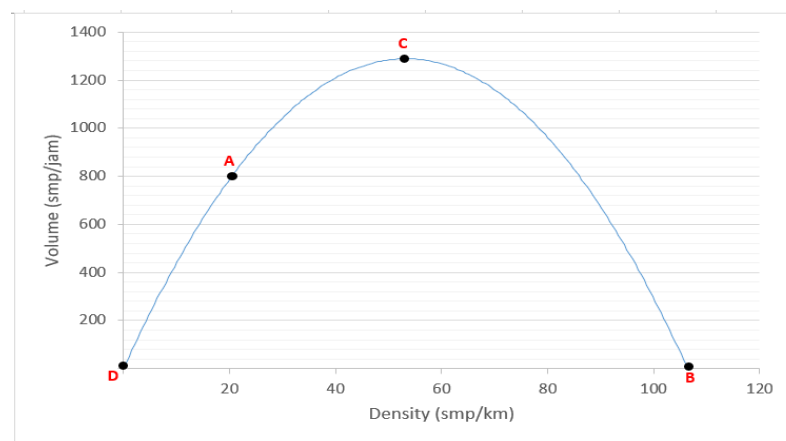


Figure 10. Volume-density curve

In Figure 10. Point D, is the condition of $V_d = 0$ and $D_d = 0$. Point C is the condition where the volume reaches its maximum value ($V = V_m$) and the maximum density ($D = D_m$) $D_m = D_j / 2 = 53.20$ pcu / km and the maximum volume value is obtained by entering the D_m value into the equation $V = 48.44D - 0.455D^2$, obtained $V_m = 1,288$ pcu / hour. Point B, the condition where $V_b = 0$ pcu / hour then $D_b = 106.41$ pcu / km and point A is assumed based on traffic flow during peak hours, namely $V_a = 802.12$ pcu / hour and $D_a = 20.51$ pcu / km. The volume, velocity, and density values at Points B, D, C were obtained from the results of the mathematical relationship analysis of the volume, velocity, and density of the Greenshield model on Monday, February 24, 2025.

The shock wave value at the intersection arm

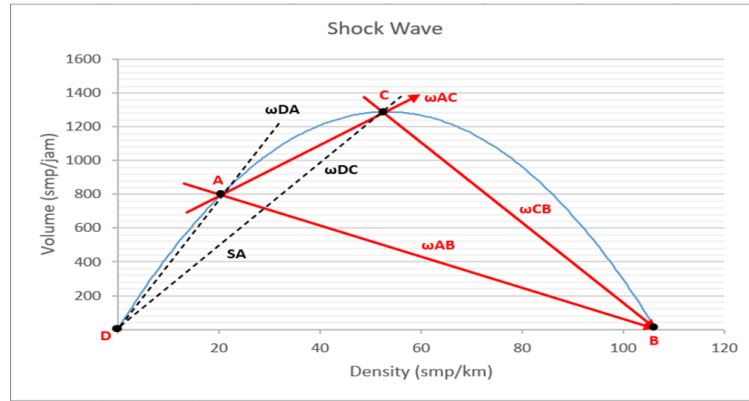


Figure 11. Shock waves on the intersection arm

From the figure, it can be seen that at the time between t_1 and t_2 , the green light is on so that the traffic flow on the intersection arm moves past the intersection towards the downstream with condition A (V_A , D_A and S_A). At time t_2 the traffic light turns red and the traffic flow condition at the stop-line changes to condition B, while the traffic flow condition after the intersection towards the downstream is in condition D, three shock waves formed starting from t_1 on the stop line are ω_{DA} , ω_{DB} and ω_{AB} .

$$\begin{aligned}\omega_{DA} &= \frac{V_A - V_D}{D_A - D_D} = S_A \\ \omega_{DA} &= \frac{802.12 - 0}{20.51 - 0} = 39.10 \text{ km/hour} \\ \omega_{DB} &= \frac{V_B - V_D}{D_B - D_D} = S_B \\ \omega_{DB} &= \frac{0 - 0}{106.41 - 0} = 0 \text{ km/hour} \\ \omega_{AB} &= \frac{V_B - V_A}{D_B - D_A} \\ \omega_{AB} &= \frac{0 - 802.12}{106.41 - 20.51} = -9.337 \text{ km/hour}\end{aligned}$$

The negative sign in the shock wave calculation above indicates that the shock wave moves backwards in the opposite direction to the movement of the traffic flow. ω_{AB} is a backward shock wave formed behind the stop line.

When the t_2 light changes from red to green, a traffic flow will form a new condition, namely the traffic flow condition C where the traffic flow at the stop line will increase from 0 (zero) to saturated. Thus causing 2 (two) new shock waves, namely ω_{DC} and ω_{CB} .

$$\begin{aligned}\omega_{DC} &= \frac{V_C - V_D}{D_C - D_D} \\ \omega_{DC} &= \frac{1.288 - 0}{53.2 - 0} = 24.226 \text{ km/hour} \\ \omega_{DC} &\text{ is a forward-moving shock wave that occurs in front of the stop line.} \\ \omega_{CB} &= \frac{V_B - V_C}{D_B - D_C}\end{aligned}$$

$$\omega_{CB} = \frac{0-1.288}{106.41-53.2} = -24.218 \text{ km/hour}$$

ω_{CB} is the recovery backward shock wave that occurs at the stop line. Traffic flow with conditions D, C, B and S continues to occur until ω_{AB} and ω_{CB} reach t_3 .

The time interval between t_2 and t_3 can be calculated using the equation. Where, r is the effective duration (seconds) of the red light.

$$t_3 - t_2 = r \cdot \frac{\omega_{AB}}{\omega_{CB} - \omega_{AB}}$$

$$t_3 - t_2 = 175 \cdot \frac{-9.337}{-24.281 - (-9.337)}$$

$$t_3 - t_2 = 109.340 \text{ second}$$

The maximum queue length (ASAM) can occur when the time is t_3 and can be calculated using the following equation where r is the effective duration of the red light (seconds)

$$QM = \frac{r}{3600} \times \frac{\omega_{CB} \cdot \omega_{AB}}{\omega_{CB} - \omega_{AB}}$$

$$QM = \frac{175}{3600} \times \frac{-24.218 \cdot (-9.337)}{-24.218 - (-9.337)}$$

$$QM = -0.739 \text{ km} = 738.67 \text{ meter}$$

When time t_3 , 1 (one) new shock wave is formed, namely the forward motion shock wave (ω_{AC}) while 2 (two) backward motion shock waves ω_{AB} and ω_{CB} end. The shock wave ω_{AC} can be calculated using the following equation.

$$\omega_{AC} = \frac{VC-VA}{DC-DA}$$

$$\omega_{AC} = \frac{1288.843-802.12}{106.41-53.2} = 14.889 \text{ km/hour}$$

The positive sign indicates that the shock wave is moving forward. Traffic flow in conditions D, C and A will continue to occur until t_5 , which is when the red light is on. At time t_4 , the forward shock wave (ω_{AC}) intersects the stop line and the traffic flow at the stop line changes from the maximum traffic flow VC to VA .

The time from the start of the green light to (t_2) to (t_4) can be calculated using the equation.

$$t_4 - t_2 = \frac{r \cdot \omega_{AB}}{\omega_{CB} - \omega_{AB}} \cdot \frac{\omega_{CB}}{\omega_{AB}} + 1$$

$$t_4 - t_2 = \frac{175 \cdot (-9.337)}{-24.218 - (-9.337)} \cdot \frac{-24.218}{-9.337} + 1 = 101.024 \text{ second}$$

$t_4 - t_2 = T$ namely the normalization time, is the total time between when the lane normalization is implemented until the queue ends.

CONCLUSION

Based on the results of the discussion of the Shock Wave Analysis study at Signalized Intersections (Semplak Intersection, Bogor City), the conclusions obtained are: 1) According to the results of the analysis obtained from the mathematical relationship between volume, speed and density, obtained from the coefficient of determination (R^2) value which is 0.2973, 2) From the results of the mathematical relationship taken between the Volume and Density of the Greenshield model to analyze the queue length using the shock wave value, the maximum volume (VM) is 1288.843 smp/hour, the maximum density (DM) is 53.2091 smp/km and the current condition is taken $VA = 802.12$ smp/hour which experiences a delay of 175 seconds, the queue length (QM) is 738.67 meters and the normalization time required is 101.024 seconds higher than the duration of the green light which is 70 seconds. This means that when the light changes from green to red, not all vehicles in the queue cross the stop line. It can also be seen that the normalization time is greatly influenced by the size of the traffic flow, the length of the delay and the length of the queue that occurs.

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