Shock Wave Analysis at Signalized Intersections (Case Study: Jl. R. Saleh S. Bustaman-Jl. Raden Aria Wiranata)

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| Submitted: March 18, 2025 | Revised: March 16, 2026 | Accepted: May 16, 2026 |

| Published: May 25, 2026 |

ABSTRACT

This study analyzes shock waves at a three-signal intersection on Jalan R. Saleh S. Bustaman and Jalan Raden Aria Wiranata, which is a crucial point in traffic flow in urban areas. Population growth and urbanization increase the need for transportation infrastructure improvements. This study aims to understand the effect of traffic signals on vehicle flow, density, and speed, and analyze the queue lengths that occur during traffic light changes. The research method uses direct observation to collect data on traffic flow, vehicle speed, and traffic light duration. The results of the analysis show a mathematical relationship between the flow, density and highest speed at the research location, obtained maximum density (Dm) on Friday of 173.14 smp / km, Maximum speed (Sm) of 6.193 km / hour, Maximum volume (Vm) of 1072 smp / hour and taken the condition of the flow VA = 628.8 smp / hour which experienced a delay of 105 seconds obtained the queue length (Qm) is 78 meters and the normalization time required is 0.013 seconds much smaller than the duration of the green light which is 25 seconds. This means that when the light changes from green to red all vehicles queuing have passed the stop line. The performance of traffic lights until compared to the condition VA = 847.2 smp / hour experienced a queue length of 4300.86 meters and required a normalization time of 9.01 seconds which is still smaller than the duration of the green light of 25 seconds. This means that when the light changes green to red all vehicles queuing have passed the stop line. The conclusion of this study confirms that efficient traffic signal management can reduce congestion and improve road safety.

Keywords: shockwave, queue length, intersection, normalization time.

INTRODUCTION

Transportation systems play a crucial role in supporting the development and progress of a region. Rapid population growth and urbanization have increased the number of road users, creating an urgent need for improvements and upgrades to transportation infrastructure. In many countries, including Indonesia, the challenges of managing traffic flow are increasingly complex, particularly in urban areas [1-3]. Problems such as congestion, traffic accidents, and inconvenience to road users often arise from ineffective traffic management. Shockwaves are a common phenomenon at signalized intersections, where sudden changes in traffic signals cause changes in vehicle speeds and unstable queues. Therefore, a thorough understanding of shockwaves is crucial for designing better traffic management systems [4-8]. This study focuses on shockwave analysis at a three-signalized intersection on Jalan R. Saleh S. Bustaman and Jalan Raden Aria Wiranata. This intersection is a crucial point for traffic flow, connecting several main routes and often experiencing congestion, especially when traffic lights change. Using shockwave analysis, this study aims to identify vehicle movement patterns, queue lengths, and vehicle reaction times to traffic signal changes. The results of this analysis are expected to provide insight into the impact of signal regulation on traffic safety and efficiency, as well as provide recommendations for improving the existing traffic management system. The objectives of this research are to determine the extent to which roads influence traffic flow, speed, and density at the study location, to analyze the mathematical relationship between flow, density, and speed at signalized intersections at the study location, and to analyze the queue lengths caused by traffic lights at this three-signaled intersection based on shock wave analysis using the greenshield model.

pISSN 2302-4240
eISSN 2655-2086
Volume 15, Issue 2, June 2026, pp.0446-0462
DOI: http://dx.doi.org/10.32832/astonjadro.v15i2.19352 http://ejournal.uika-bogor.ac.id/index.php/ASTONJADRO

Intersection Theory

An intersection is a node in the road network where roads meet and vehicle traffic flows intersect.

Intersection Types

a. At-Grade Intersection

An at-grade intersection is where roads meet or intersect in one plane.

b. Non-At-Grade Intersection

A non-at-grade intersection is where roads intersect in different planes.

The shock wave theory developed by Bruce D. Greenshields explains the movement of traffic disturbances along a roadway due to changes in traffic flow, speed, and density. In transportation engineering, a shock wave occurs when there is a sudden variation in traffic conditions, such as congestion, vehicle queues, accidents, traffic signals, or railway crossing closures. These disturbances propagate through the traffic stream similarly to waves moving in fluids [9-10], [18].

Greenshields introduced the fundamental relationship between speed, density, and traffic flow through the linear speed–density model. According to this theory, traffic speed decreases as vehicle density increases. When traffic demand exceeds roadway capacity, vehicles slow down and form queues, creating a backward-moving shock wave. Conversely, when congestion dissipates, a forward-moving recovery wave can occur [11], [19].

The speed of a shock wave is determined by the difference in traffic flow and density between two traffic states. Mathematically, the shock wave speed is expressed as the ratio of the change in flow to the change in density. This concept is widely applied in evaluating delays, queue lengths, and congestion patterns on highways, intersections, toll gates, and railway crossings [12-13].

Shock wave analysis helps transportation planners understand traffic behavior under varying operational conditions and supports the development of traffic management strategies. The theory is particularly useful in estimating queue propagation and dissipation during peak hours or temporary road interruptions. Today, Greenshields' shock wave theory remains an important foundation in traffic flow analysis and intelligent transportation system studies [14-15], [20].

Mathematical Relationship of Traffic Volume, Speed, and Density

The mathematical relationship between speed, volume, and density can be expressed by the following equation.

$$V = D.\ S \quad (1)$$

Shows the general form of the mathematical relationship between Velocity-Density (S-D), Volume-

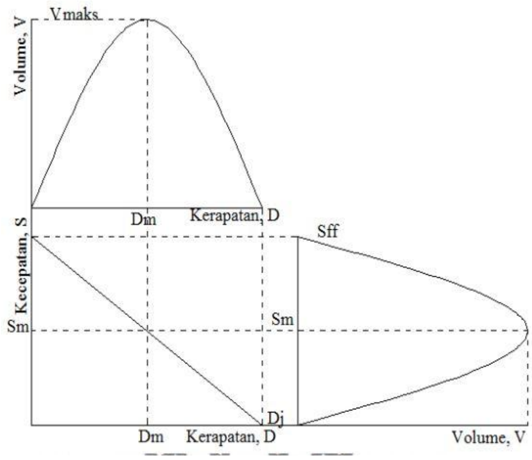

Figure 1. Mathematical relationship between velocity, flow, and density [16]

Greenshield Model

Greenshield formulated the mathematical relationship between velocity and density as assumed to be linear, as expressed by the following equation [9], [16]:

$$S = Sff - \frac{sff}{Dj} \cdot D \quad (2)$$

Where:
S: Speed
Sff: Average speed of the free-flow state space
Dj: Jam density
D: Density

Shock Wave Analysis

A shock wave is defined as the movement or passage of a change in traffic flow. Under free-flow conditions, vehicles travel at a certain speed. If this flow encounters an obstruction (disruption), there will be a reduction in the flow that can pass through the obstruction. This obstruction to traffic flow can be in the form of a partial or complete lane closure on a road section, for example, due to an accident or road repairs, or it can also be caused by an obstruction at a red light at a traffic light intersection. A shock wave can be described as a movement in traffic flow resulting from changes in density and traffic flow.

Shock Waves at Traffic Light Intersections

This study examines the phenomenon of shock waves at traffic intersections, assuming relatively low and constant traffic flow. When the capacity of the intersection arm is greater than the traffic flow, vehicles are not blocked when the green light is on, creating a free-flow condition around the traffic light. However, when the red light is on, a discontinuity occurs, where oncoming vehicles join the stopped vehicles in the queue. This situation produces two types of shock waves: a backward shock wave formed when the red light is on, resulting in increased traffic congestion due to queues; a second type of shock wave, a backward recovery shock wave, occurs when the light turns green, which reduces the queue congestion as vehicles begin to move. In addition, a stationary shock wave occurs at the stop line during the red light.

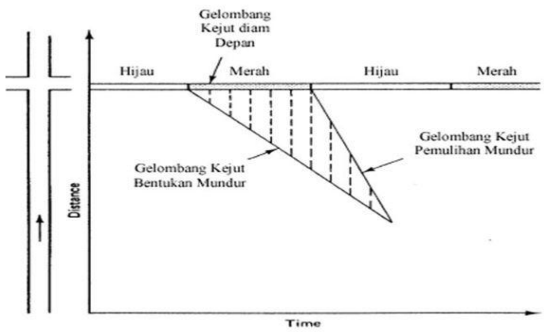

Figure 2. Manifestation of shock waves at intersections with traffic lights [16]

RESEARCH METHODOLOGY
Research Flow Chart

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pISSN 2302-4240
eISSN 2655-2086

Volume 15, Issue 2, June 2026, pp.0446-0462
DOI: http://dx.doi.org/10.32832/astonjadro.v15i2.19352 http://ejournal.uika-bogor.ac.id/index.php/ASTONJADRO

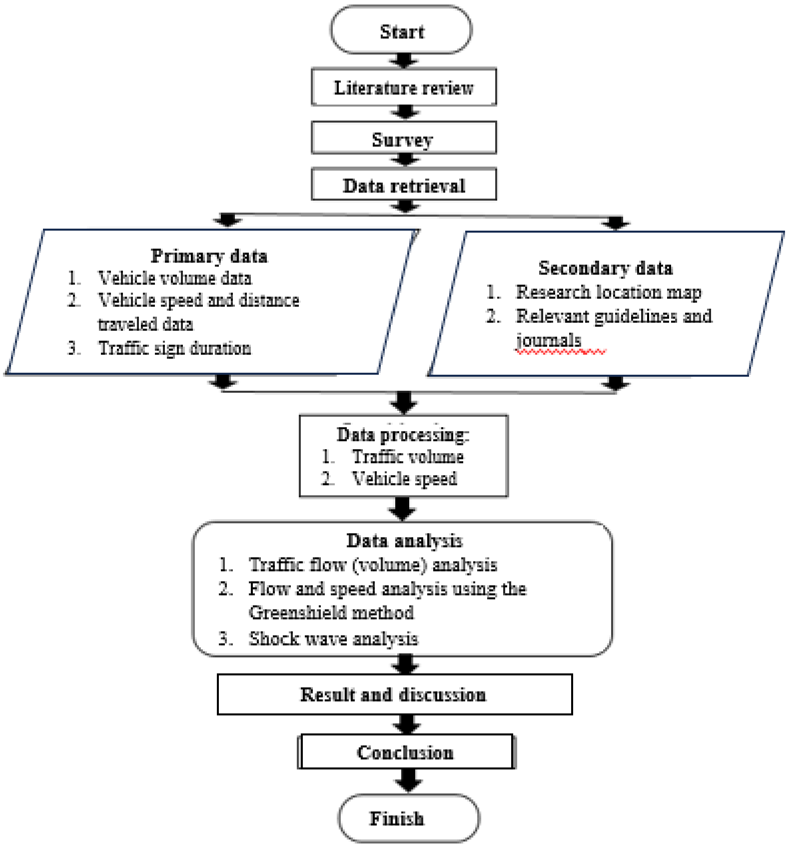

Figure 3. Flowchart

Data Collection

This survey was conducted at the intersection under study, but only on one side of the road: the one leading from BTM/Bogor Botanical Gardens, from Jl. R. Saleh S. Bustaman to Jl. Raden Aria Wiranata.

Figure 4. Research Location Source: Google Map, 2025

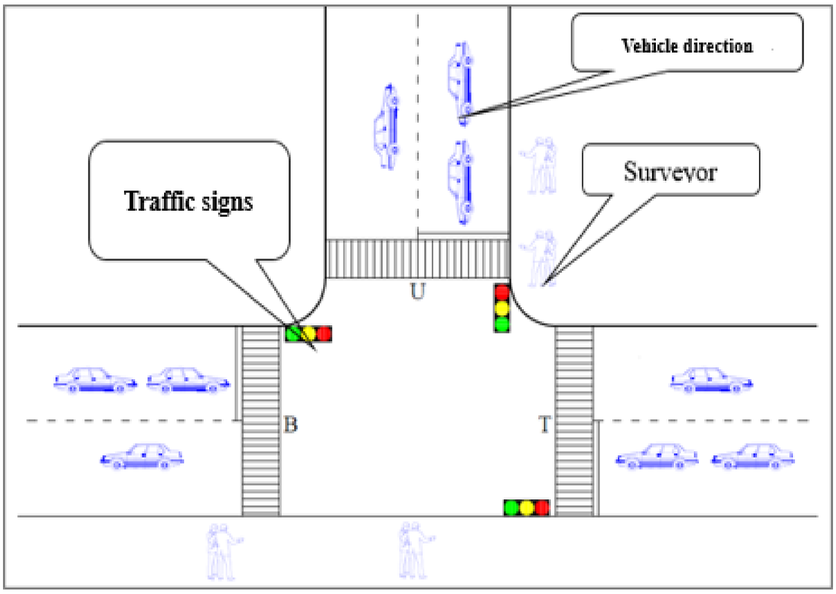

Figure 5. Sketch of the traffic flow surveyor's position, speed, and traffic light duration at a four-arm intersection. Source: Processed Data, 2025

RESEARCH METHODS

Shock Wave Values at Signalized Intersections

During the time between t0 and t1, the green light is on, causing traffic on the intersection arm to move downstream through the intersection in condition A (VA, DA, and SA). At time t1, the traffic light changes to red, and the traffic flow at the stop line changes to condition B, while the traffic flow after the intersection downstream is in condition D. The three shock waves that form starting at t1 at the stop line are as follows:

$$\omega DA = \frac{VA-VD}{DA-DD} = SA \quad (3)$$

$$\omega DB = \frac{VB-VD}{DB-DD} = 0 \quad (4)$$

$$\omega AB = \frac{VB-VA}{DB-DA} = -\frac{VA}{DB-DA} \quad (5)$$

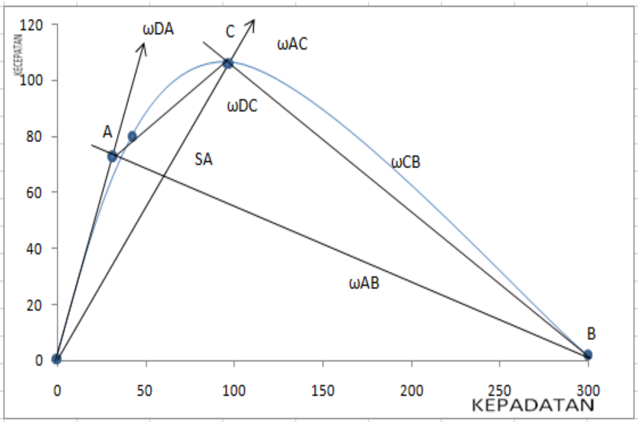

Figure 6. Speed current curve of a junction arm [16]

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eISSN 2655-2086
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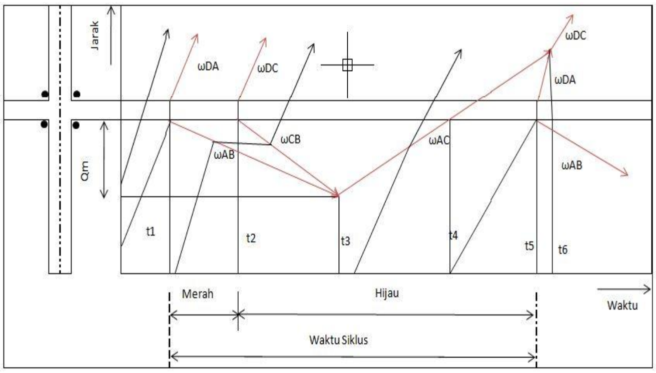

Figure 7. Time-Distance Diagram [16]

The speed of the new shock wave can be calculated using the following equation:

$$\omega DC = \frac{VC-VD}{DC-DD} = SC \quad (6)$$

$$\omega CB = \frac{VC-VB}{DB-DC} = -\frac{VC}{DB-DC} \quad (7)$$

Traffic flow with conditions D, C, B, and A continues until ωAB and ωCB reach t3. The time interval between t2 and t3 can be calculated using the equation below.

$$t3 - t2 = r\,.\,\left|\frac{\omega AB}{\omega CB-\omega AB}\right| \quad (8)$$

Where r is the effective duration of the red light (seconds). The maximum queue length will occur at time t3 and can be calculated using the following equation.

$$QM = \frac{r}{3600}\left|\frac{\omega CB\,.\,\omega AB}{\omega CB-\omega AB}\right| \quad (9)$$

At time t3, 1 (one) new shock wave is formed, namely the forward motion shock wave (ωAC), while 2 (two) backward motion shock waves ωAB and ωCB end. The shock wave ωAC is shown in the figure above and can be calculated using the following equation:

$$\omega AC = \frac{VC-VA}{DC-DA} \quad (10)$$

Traffic flow in conditions D, C, and A continues until t5, which is when the red light is on. At time t4, the forward motion shock wave ωAC crosses the stop line and the traffic flow at the stop line changes from the maximum traffic flow VC to VA. It can be said that at time t4 all vehicles have crossed the stop line. The time between the start of the green light (t2) and (t4) can be calculated using the following equation:

$$t4 - t2 = \frac{r\,.\,\omega CB}{(\omega CB-\,\omega AB\,)}.\left|\frac{\omega CB}{\omega AC}+1\right| \quad (11)$$

(t4-t2) = T is called the normalization time, which is the total time between the implementation of lane normalization and the end of the queue.

Linear Regression Analysis

Linear regression analysis is a statistical method that can be used to study the relationship between the characteristics of the problem being investigated. The linear regression analysis model can model the relationship between two or more variables. In the simplest case,

Y = A + B. X (12)

Where:
Y = Dependent variable, X = Independent variable
A = Regression constant, B = Regression coefficient

The magnitudes of the constants A and B can be found using the equations below.

$$B = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{n(\Sigma x^2) - (\Sigma x)^2} \qquad A = \frac{\Sigma Y - B \Sigma X}{n} \tag{13}$$

DISCUSSION

Traffic Light Cycle

The duration of the traffic light cycle at the research location.
Traffic volume is calculated using the Passenger Car Equivalent (EMP) of each vehicle [17], as follows:

1. Heavy Vehicles (HV) = 1.3 EMP
2. Light Vehicles (LV) = 1.0 EMP
3. Motorcycles (MC) = 0.4 EMP

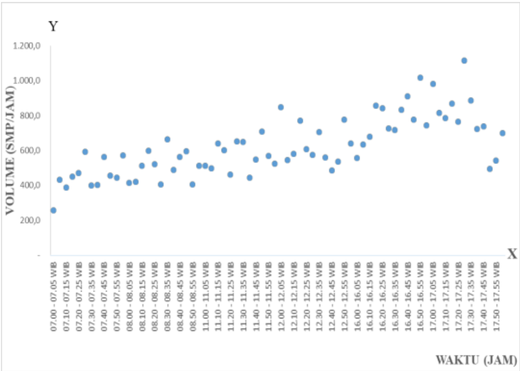

Figure 8. Saturday Volume

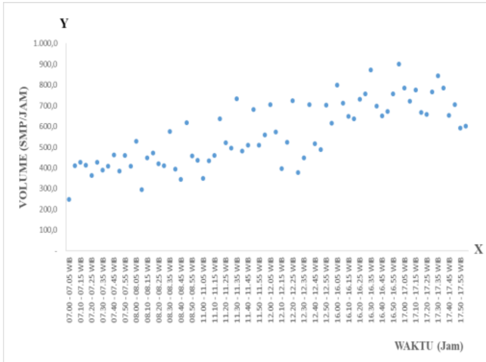

Figure 9. Sunday Volume

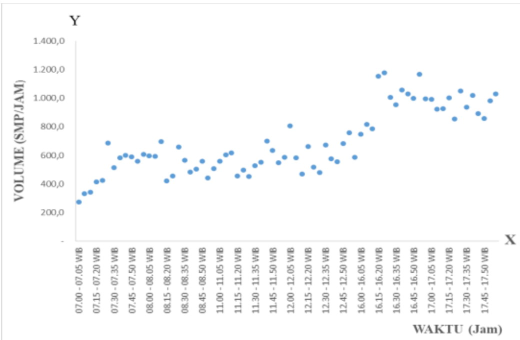

Figure 10. Monday Volume

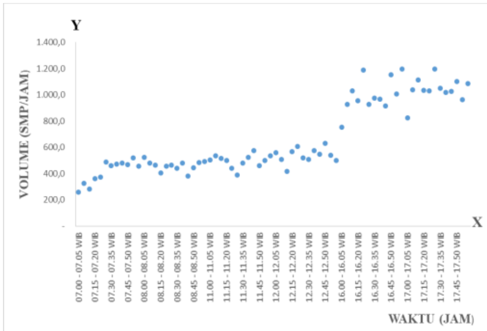

Figure 11. Friday Volume

This can be seen in the graph, showing the maximum volume on weekdays during rush hour.

Vehicle Speed Calculation

The speed variable used to analyze the relationship between speed, volume, and density is average speed. Average speed can be obtained using the following equation:

$$Ss = \frac{dn}{\Sigma ti}$$

Ss = Average speed (Km/hour)
D = Distance traveled (m)
N = Number of Vehicles
ti = Travel time of vehicle I (m/sec)

pISSN 2302-4240
eISSN 2655-2086

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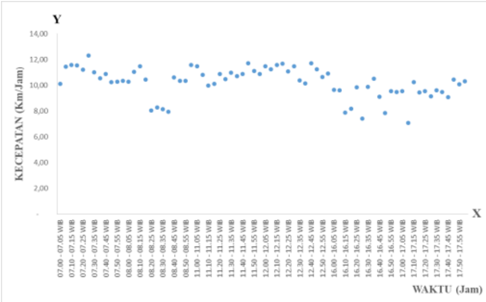

Figure 12. Saturday Speed/Density

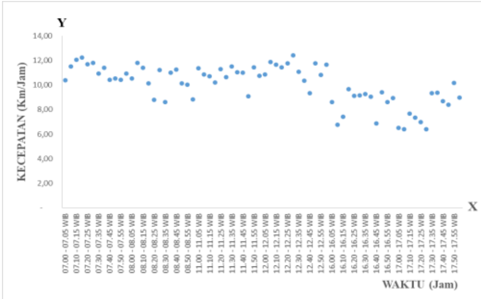

Figure 13. Sunday Speed/Density

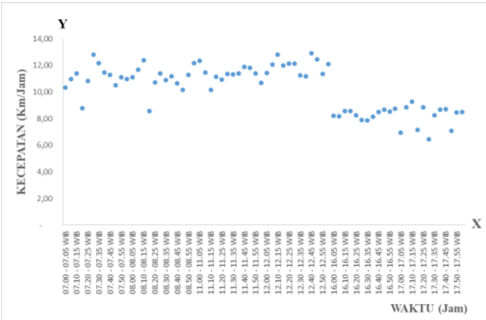

Figure 13. Speed/Density on Monday

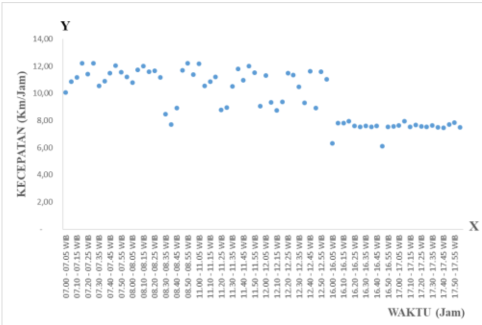

Figure 14. Speed/Density on Friday

Mathematical Relationship between Traffic Volume, Speed, and Density

The characteristic relationship between speed density, volume density, and speed volume on the study day. The graph below shows the relationship between capacity, volume, speed, and traffic density using the Greenshields model.

Model Greenshield

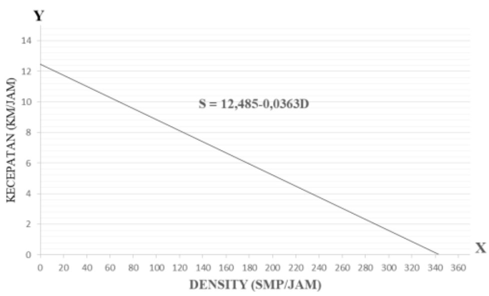

Figure 15. Speed-Density Relationship for Saturday's Greenshield Model

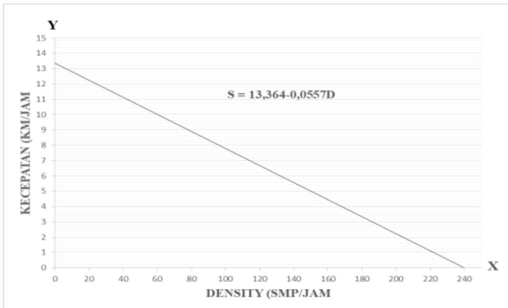

Figure 16. Speed-Density Relationship for Sunday's Greenshield Model

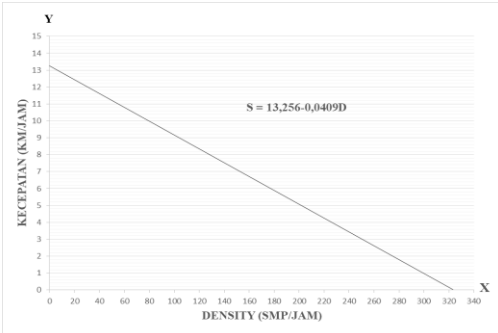

Figure 17. Speed-Density Relationship for the Greenshield Model on Monday

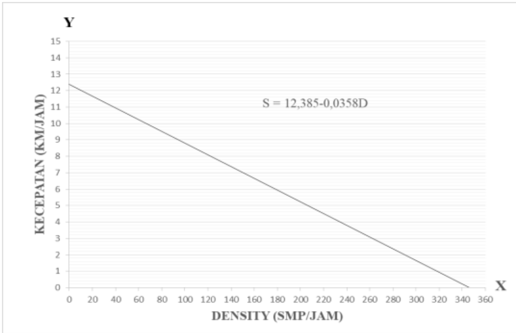

Figure 18. Speed-Density Relationship for the Greenshield Model on Friday

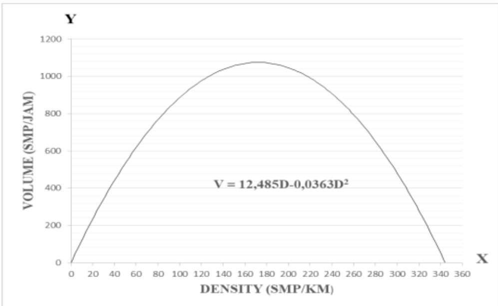

Figure 19. Volume – Density Relationship of Saturday's Greenshield Model

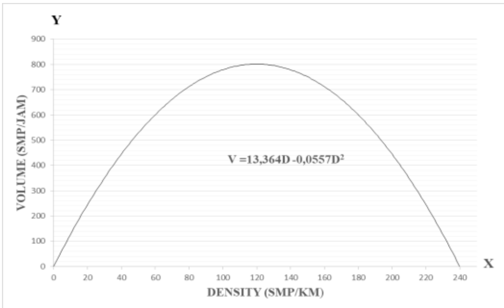

Figure 20. Volume – Density Relationship of Sunday Greenshield Model

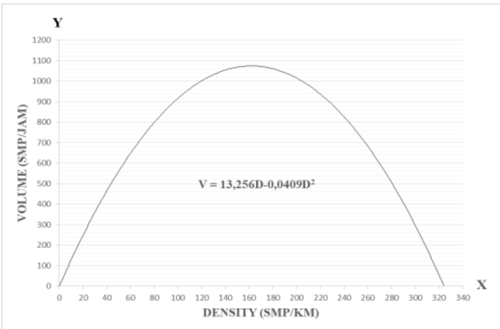

Figure 21. Volume – Density Relationship of the Greenshield Model Monday

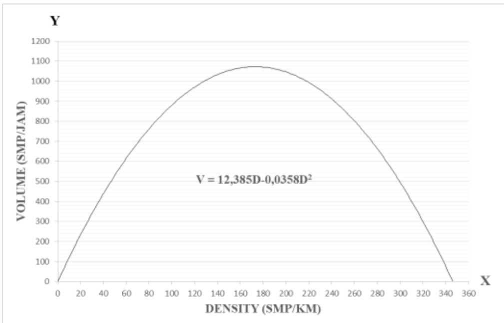

Figure 22. Volume – Density Relationship of Sunday Greenshield Model

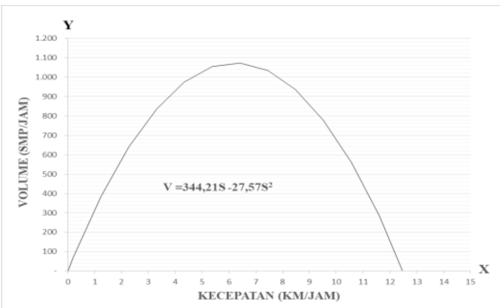

Figure 23. Saturday Greenshield Model Volume-Velocity Relationship

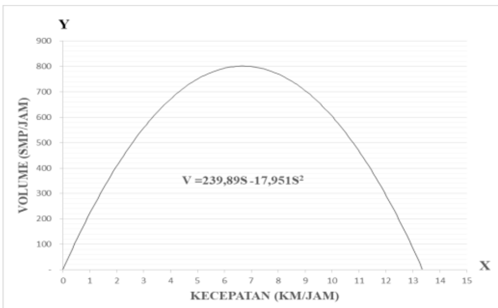

Figure 24. Sunday Greenshield Model Volume-Velocity Relationship

pISSN 2302-4240
eISSN 2655-2086
Volume 15, Issue 2, June 2026, pp.0446-0462
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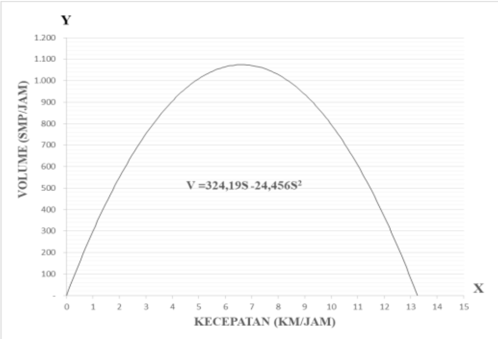

Figure 25. Volume-Velocity Relationship for Monday's Greenshield Model

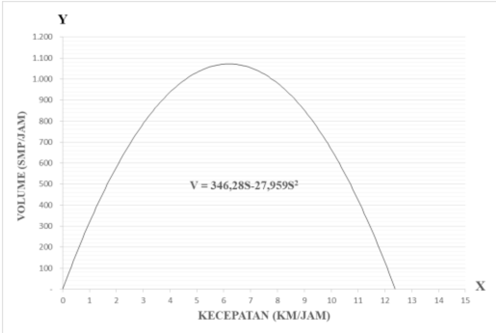

Figure 26. Volume-Velocity Relationship for Friday's Greenshield Model

The graph results from the four-day study above show that the B values obtained from the graphs above for Saturday, Sunday, Monday, and Friday are -0.0363, -0.0557, -0.0409, and -0.0358, respectively. Meanwhile, the A values obtained from these graphs are 12.485, 13.364, 13.256, and 12.385. The resulting values are:

Saturday, March 8, 2025

Sff = 12,485 km/hour
Dj $= -\frac{12,485}{(-0,0363)}$ = 343,04 Smp/km
Results of value b = $\frac{1}{-0,0363}$ = -27,55

Using the Sff and Dj values, the mathematical relationship between the parameters can be determined as follows:
Speed-density relationship S = 12.485 - 0.0363D
Volume-density relationship V = 12.485D - 0.0363D2
Volume-velocity relationship V = 344.21S - 27.57S2
The maximum volume can be calculated using the equations V = 12.485D - 0.0363D2 and V = 344.21S - 27.57S2
∂V/∂D = 0, Dm = 344.21/2 = 172.105 smp/km
∂V/∂D = 0, Sm = 12.485/2 = 6.2425 km/h
By entering the Dm value = 172.105 smp/hour to the equation V= 12.485D - 0.0363D2 or the value of Sm = 6.2425 Km/Hour to the equation V=344.21S - 27.57S2, the value of Vm = Dm x Sm = 0 will be obtained Vm=172.105 x 6.2425 = 1074.365 smp/hour. It can be concluded that the maximum volume on Saturday, March 8, 2025 occurred at a density condition of D = 172.105 smp/km moving at a speed of S=6.2425 km/hour.

Sunday, March 9, 2025

Sff = 13.364 km/h
Dj = -13.364/((-0.0557)) = 239.93 smp/km
Resulting b value = 1/(-0.0557) = -17.95
Using the Sff and Dj values, the mathematical relationship between the parameters can be determined as follows:
Speed-density relationship S = 13.364 - 0.0557D
Volume-density relationship V = 13.364D - 0.0557D2
Volume-velocity relationship V = 239.89S - 17.951S2
Therefore, the maximum volume can be calculated using the equations V = 13.364D - 0.0557D2 and V = 239.89S - 17.951S2
∂V/∂D = 0, we get Dm = 239.89/2 = 119.945 smp/km
∂V/∂D = 0, we get Sm = 13.364/2 = 6.682 km/h
By plugging the value of Dm = 119.945 smp/h into the equation V = 13.364D - 0.0557D2 or the value of Sm = 6.682 Km/Hour to the equation V=239.89S - 17.951S2, the value of Vm = Dm x Sm

= 0 will be obtained Vm=119.945 x 6.682 = 801.472 smp/h. It can be concluded that the maximum volume on Sunday, March 9, 2025 occurred at a density condition of D = 119.945 smp/km moving at a speed of S=6.682 km/h.

Monday, March 10, 2025

Sff = 13.256 km/h
Dj = -13.256/((-0.0409)) = 324.11 Smp/Km
Resulting b = 1/(-0.0409) = -24.45
Using the Sff and Dj values, the mathematical relationship between the parameters can be determined as follows:

Speed-density relationship	S = 13.256 - 0.0409D
Volume-density relationship	V = 13.256D - 0.0409D2
Volume-velocity relationship	V = 324.19S - 24.456S2

Therefore, the maximum volume can be calculated using the equations V = 13.256D - 0.0409D2 and V = 324.19S - 24.456S2
$\partial V/\partial D = 0$, Dm = 324.19/2 = 162.095 smp/km
$\partial V/\partial D = 0$, Sm = 13.256/2 = 6.628 km/h
By inserting the value of Dm = 162.095 smp/h into the equation V = 13.256D - 0.0409D2 or the value of Sm = 6.628 km/h into the equation V = 324.19S - 24.456S2, the value of Vm = Dm x Sm = 0, Vm = 162.095 x 6.628 = 1074.366 smp/h. It can be concluded that the maximum volume on Monday, March 10, 2025 occurred at a density of D = 162,095 smp/km moving at a speed of S = 6,628 km/hour.

Friday, March 14, 2025

Sff = 12.385 km/h
Dj = -12.385/((-0.0358)) = 345.95 Smp/Km
Resulting b = 1/(-0.0358) = -27.93
Using the Sff and Dj values, the mathematical relationship between the parameters can be determined as follows:

Speed-density relationship	S = 12.385 - 0.0358D
Volume-density relationship	V = 12.385D - 0.0358D2
Volume-velocity relationship	V = 346.28S - 27.959S2

Therefore, the maximum volume can be calculated using the equations V = 12.385D - 0.0358D2 and V = 346.28S - 27.959S2
$\partial V/\partial D = 0$, Dm = 346.28/2 = 173.14 smp/km
$\partial V/\partial D = 0$, Sm = 12.385/2 = 6.193 km/hour
By inserting the value of Dm = 173.14 smp/hour into the equation V = 12.385D - 0.0358D2 or the value of Sm = 6.193 km/hour into the equation V = 346.28S - 27.959S2, the value of Vm = Dm x Sm = 0 is obtained, Vm = 173.14 x 6.193 = 1072.256 smp/hour. It can be concluded that the maximum volume on Friday, March 14, 2025 occurred at a density of D = 173.14 smp/km moving at a speed of S = 6.193 km/hour.

Shock Wave Value at Traffic Light Intersections

Shock waves at traffic lighted intersections can be analyzed if the mathematical relationship between the flow density for the intersection arm is known and the traffic flow conditions have been determined. To calculate the shock wave value, a mathematical relationship between speed – density, volume – density and volume – speed has been calculated.

Mathematical Relationship on Saturday, March 8, 2025.

Velocity-density relationship	S = 12.485 – 0.0363D
Volume-density relationship	$V = 12.485 – 0.0363D^2$
Volume-velocity relationship	$V = 344.21S – 27.57S^2$

Mathematical Relationship on Sunday, March 9, 2025

Velocity-density relationship	S = 13.364 - 0.0557D

pISSN 2302-4240
eISSN 2655-2086
Volume 15, Issue 2, June 2026, pp.0446-0462
DOI: http://dx.doi.org/10.32832/astonjadro.v15i2.19352 http://ejournal.uika-bogor.ac.id/index.php/ASTONJADRO

Volume-density relationship	$V = 13.364D - 0.0557D^2$
Volume-velocity relationship	$V = 239.89S - 17.951S^2$

Mathematical Relationship on Monday, March 10, 2025

Relationship Speed-density relationship

	S = 13.256 - 0.0409D
Volume-density relationship	V = 13.256D - 0.0409D2
Volume-velocity relationship	V = 324.19S - 24.4561S2

Mathematical relationship on Friday, March 14, 2025

Speed-density relationship	S = 12.385 - 0.0358D
Volume-density relationship	V = 12.385D - 0.0358D2
Volume-velocity relationship	V = 346.285S - 27.959S2

When the flow or volume condition is D, VD = 0 smp/hour, then DD = 0 smp/km. The condition at maximum flow or volume (VC) is obtained using the following equation:

Saturday

VC = 12.485 x 0.0363 x 344.21 x 27.57 = 4300.86 smp/hour
DC = e^(Ln12.485-1) = 11.485 Maximum density condition.
VB = 0 smp/hour, volume flow condition B, then DB = 344.
For VA conditions, assumed from value (0) to the largest maximum volume:
VA = 847.2 smp/hour, DA = 94
VC = 4300.86 smp/hour, Dc = 11.485
VB = 0 smp/hour, DB = 344
VD = 0 smp/hour, DD = 0 smp/hour

Sunday

VC = 13.364 x 0.0557 x 239.89 x 17.951 = 3200.12 smp/hour
DC = e^(Ln13.364-1) = 12.364, maximum density condition.
VB = 0 smp/hour, volume flow condition B, then DB = 240.
For VA conditions, assumed from value (0) to the largest maximum volume:
VA = 733.2 smp/hour, DA = 86
VC = 3200.12 smp/hour, Dc = 12,364
VB = 0 smp/hour, DB = 240
VD = 0 smp/hour, DD = 0 smp/hour

Monday

VC = 13.256 x 0.0409 x 324.195 x 24.456 = 4298.61 smp/hour
DC = e^(Ln13.256-1) = 12.256, maximum density condition.
VB = 0 smp/hour, volume flow condition B, then DB = 13.
For VA conditions, assumed from value (0) to the largest maximum volume:
VA = 806.4 smp/hour, DA = 84
VC = 4298.61 smp/hour, Dc = 12.256
VB = 0 smp/hour, DB = 324
VD = 0 smp/hour, DD = 0 smp/hour

Friday

VC = 12.385 x 0.0358 x 346.285 x 27.959 = 4256.77 smp/hour
DC = e^(Ln12.385-1) = 11.385, maximum density condition.
VB = 0 smp/hour, volume flow condition B, then DB = 12.
For VA conditions, assumed from value (0) to the largest maximum volume:
VA = 628.8 smp/hour, DA = 63
VC = 4256.77 smp/hour, Dc = 11,385
VB = 0 smp/hour, DB = 346
VD = 0 smp/hour, DD = 0 smp/hour.

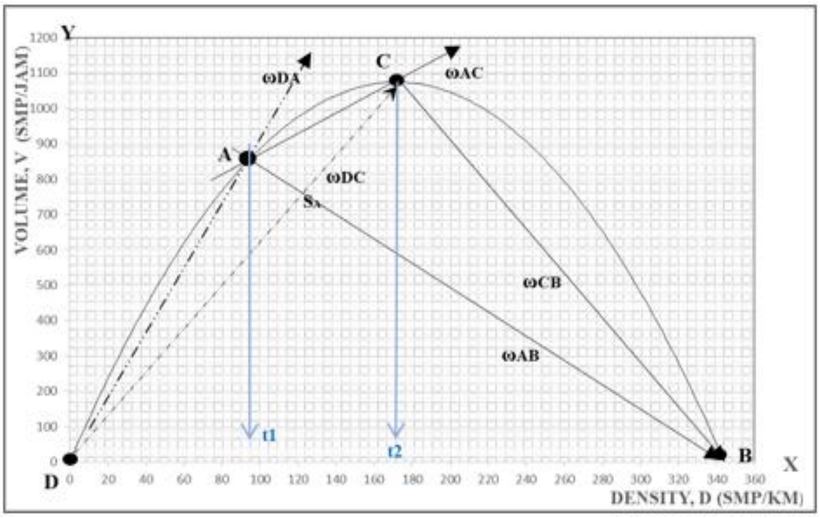

Figure 27. Shock wave at an intersection Source: Processed data, 2025

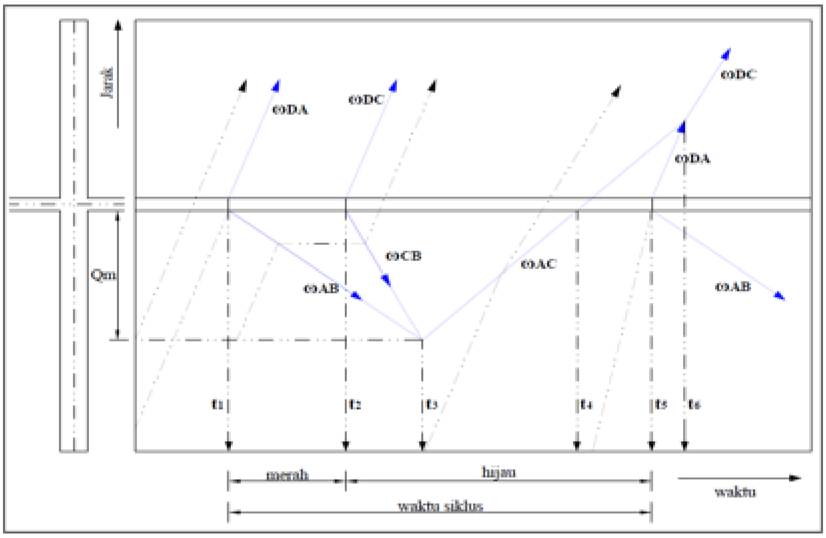

Figure 28. Shock waves at a traffic light intersection. Source: Processed data, 2025

Figure 28 shows that, between t1 and t2, the green light is on, causing traffic flow on the intersection arm to move downstream. The traffic flow at the stop line changes to condition B. The traffic flow after the intersection, downstream, changes to condition D. Three shock waves formed starting at t1 at the stop line are ωDA, ωDB, and ωAB at the study location. The effective red-light duration (r) = 105 seconds is the same for each study day, and the volume values for each study day are:

1. Volume (V) = 4300.86 pcu/hour (Saturday)
2. Volume (V) = 3200.12 pcu/hour (Sunday)
3. Volume (V) = 4298.61 pcu/hour. (Monday)
4. Volume (V) = 4256.77 smp/hour. (Friday)

1. $\omega DA = \frac{VA-VD}{DA-DD} = \frac{847{,}2-0}{94-0} = 9{,}01\ \text{smp/hours}$
2. $\omega DA = \frac{VA-VD}{DA-DD} = \frac{733{,}2-0}{86-0} = 8{,}53\ \text{smp/hours}$
3. $\omega DA = \frac{VA-VD}{DA-DD} = \frac{806{,}4-0}{84-0} = 9{,}6\ \text{smp/hours}$

Volume 15, Issue 2, June 2026, pp.0446-0462
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4. $\omega DA = \frac{VA-VD}{DA-DD} = \frac{628{,}8-0}{63-0} = 9{,}98 \text{ smp/hours}$

A positive value indicates a forward shock wave that is in the direction of traffic movement. ωDA is the forward shock wave that occurs ahead of the stop line. ωDB is the front stationary shock wave that occurs at the stop line.

$\omega DB = \frac{VB-VD}{DB-DD} = \frac{0-0}{0-0} = 0\ km/hours.$

1. $\omega AB = \frac{VB-VA}{DB-DA} = -\frac{0-847{,}2}{344-94} = -3{,}388$ km/hours
2. $\omega AB = \frac{VB-VA}{DB-DA} = -\frac{0-733{,}2}{240-86} = -4{,}761$ km/hours
3. $\omega AB = \frac{VB-VA}{DB-DA} = -\frac{0-806{,}4}{324-84} = -3{,}36$ km/hours
4. $\omega AB = \frac{VB-VA}{DB-DA} = -\frac{0-628{,}8}{346-63} = -2{,}222$ km/hours

A negative sign indicates that the shock wave moves backward in the opposite direction to the traffic flow. ωAB is a backward shock wave formed behind the stop line. At time t2, when the light changes from red to green, a new traffic flow condition will be formed, namely traffic flow in condition C, where the traffic flow at the stop line will increase from 0 (zero) to saturated. This causes two new shock waves, namely ωCB.

1. $\omega DC = \frac{VC-VD}{DC-DD} = \frac{4300{,}86-0}{11{,}485-0} = 374{,}476\ km/hours$
2. $\omega DC = \frac{VC-VD}{DC-DD} = \frac{3200{,}12-0}{12{,}364-0} = 258{,}825\ km/hours$
3. $\omega DC = \frac{VC-VD}{DC-DD} = \frac{4298{,}61-0}{12{,}256-0} = 370{,}735\ km/hours$
4. $\omega DC = \frac{VC-VD}{DC-DD} = \frac{4256{,}77-0}{11{,}385-0} = 373{,}892\ km/hours$

1. $\omega CB = \frac{VC-VB}{DB-DC} = -\frac{4300{,}86}{344-11{,}485} = -12{,}93\ km/hours$
2. $\omega CB = \frac{VC-VB}{DB-DC} = -\frac{3200{,}12}{240-12{,}364} = -14{,}06\ km/hours$
3. $\omega CB = \frac{VC-VB}{DB-DC} = -\frac{4298{,}61}{324-12{,}256} = -13{,}79\ km/hours$
4. $\omega CB = \frac{VC-VB}{DB-DC} = -\frac{4256{,}77}{346-11{,}385} = -12{,}72\ km/hours$

ωCB is the recovery backward shock wave that occurs at the stop line. Traffic flows with conditions D, C, B, and S continue until ωAB and ωCB reach t3. The time interval between t2 and t3 can be calculated using the following equation.

1. $t3 - t2 = r\ .\ \left|\frac{\omega AB}{\omega CB-\omega AB}\right| = 105\ .\ \left|\frac{-3{,}388}{-12{,}93-3{,}388}\right| = 21{,}8\ second$
2. $t3 - t2 = r\ .\ \left|\frac{\omega AB}{\omega CB-\omega AB}\right| = 105\ .\ \left|\frac{-4{,}761}{-14{,}06-4{,}761}\right| = 26{,}56 \text{ second}$
3. $t3 - t2 = r\ .\ \left|\frac{\omega AB}{\omega CB-\omega AB}\right| = 105\ .\ \left|\frac{-3{,}36}{-13{,}79-3{,}36}\right| = 20{,}57 \text{ second}$
4. $t3 - t2 = r\ .\ \left|\frac{\omega AB}{\omega CB-\omega AB}\right| = 105\ .\ \left|\frac{-2{,}222}{-12{,}72-2{,}222}\right| = 15{,}61 \text{ second}$

The maximum queue length (QM) will occur at time t3 and can be calculated using the following equation where r is the effective duration of the red light (seconds).

1. $QM = \frac{r}{3600}\left|\frac{\omega CB\ .\ \omega AB}{\omega CB-\omega AB}\right| = \frac{105}{3600}\left|\frac{12{,}93\ .3{,}388}{12{,}93-3{,}388}\right| = 0{,}133\ km =$ 133m
2. $QM = \frac{r}{3600}\left|\frac{\omega CB\ .\ \omega AB}{\omega CB-\omega AB}\right| = \frac{105}{3600}\left|\frac{14{,}06\ .\ 4{,}761}{14{,}06-4{,}761}\right| = 0{,}209\ km =$ 209m
3. $QM = \frac{r}{3600}\left|\frac{\omega CB\ .\ \omega AB}{\omega CB-\omega AB}\right| = \frac{105}{3600}\left|\frac{13{,}79\ .\ 3{,}36}{13{,}79-3{,}36}\right| = 0{,}129\ km =$ 129m
4. $QM = \frac{r}{3600}\left|\frac{\omega CB\ .\ \omega AB}{\omega CB-\omega AB}\right| = \frac{105}{3600}\left|\frac{12{,}72\ .\ 2{,}222}{12{,}72-2{,}222}\right| = 0{,}078\ km =$ 78m

At time t3, a new shock wave is formed, namely: the forward motion shock wave (ωAC), while the two backward motion shock waves ωAB and ωCB end. The shock wave ωAC can be calculated using the equation:

1. $\omega AC = \frac{VC-VA}{DC-DA} = \frac{4300{,}12-847{,}2}{374{,}476-94} = 12{,}31$ km/hour
2. $\omega AC = \frac{VC-VA}{DC-DA} = \frac{3200{,}12-733{,}2}{258{,}825-86} = 14{,}274$ km/hour
3. $\omega AC = \frac{VC-VA}{DC-DA} = \frac{4298{,}61-806{,}4}{370{,}735-84} = 12{,}179$ km/hour
4. $\omega AC = \frac{VC-VA}{DC-DA} = \frac{4256{,}77-628{,}8}{373{,}892-63} = 11{,}669$ km/hour

Traffic flow in conditions D, C, and A continues until t5, which is when the red light is on. At time t4, the forward motion shock wave (ωAC) cuts the stop line changing from the maximum traffic flow VC to VA. The time between the start of the green light (t2) to (t4) can be calculated using the equation:

$$t4 - t2 = \frac{r\,.\,\omega AB}{(\omega CB - \omega AB)} . \left|\frac{\omega CB}{\omega AC} + 1\right|$$

$$= \frac{\left(\frac{105}{3600}\right).(-3{,}388)}{(-12{,}93 - 3{,}388)} . \left|\frac{12{,}93}{12{,}31} + 1\right| = 0{,}021\ second$$

$$= \frac{\left(\frac{105}{3600}\right).(-4{,}761)}{(-14{,}06 - 4{,}761)} . \left|\frac{14{,}06}{14{,}274} + 1\right| = 0{,}029 \text{ second}$$

$$= \frac{\left(\frac{105}{3600}\right).(-3{,}36)}{(-13{,}79 - 3{,}36)} . \left|\frac{13{,}79}{12{,}179} + 1\right| = 0{,}020 \text{ second}$$

$$= \frac{\left(\frac{105}{3600}\right).(-2{,}222)}{(-12{,}72 - 2{,}222)} . \left|\frac{12{,}72}{11{,}669} + 1\right| = 0{,}013 \text{ second}$$

t4-t2 = T, which is the normalization time, is the total time between the implementation of lane normalization and the end of the queue.

Discussion

According to the analysis results, the mathematical relationship between flow, speed, and density at the signalized intersection at the location during the four days of the study is as follows:

a. Mathematical relationship on Saturday, March 8, 2025.

Speed-density relationship	S = 12.485 – 0.0363D
Volume-density relationship	V = 12.485 – 0.0363D²
Volume-speed relationship	V = 344.21S – 27.57S²

b. Mathematical Relationship on Sunday, March 9, 2025

Velocity-density relationship	S = 13.364 - 0.0557D
Volume-density relationship	V = 13.364D - 0.0557D2
Volume-velocity relationship	V = 239.89S - 17.951S2

c. Mathematical Relationship on Monday, March 10, 2025

Velocity-density relationship	S = 13.256 - 0.0409D
Volume-density relationship	V = 13.256D - 0.0409D2
Volume-velocity relationship	V = 324.19S - 24.4561S2

d. Mathematical Relationship on Friday, March 14, 2025

Velocity-density relationship	S = 12.385 - 0.0358D
Volume-density relationship	V = 12.385D - 0.0358D2
Volume-velocity relationship	V = 346.285S - 27.959S2

CONCLUSION

From the results of the mathematical relationship taken between volume and density in the greenshield model to analyze the queue length using the shock wave value on Saturday, the maximum volume (Vm) is 1074.365 smp/hour, the maximum density (Dm) is 172.105 smp/km, the

pISSN 2302-4240
eISSN 2655-2086
Volume 15, Issue 2, June 2026, pp.0446-0462
DOI: http://dx.doi.org/10.32832/astonjadro.v15i2.19352 http://ejournal.uika-bogor.ac.id/index.php/ASTONJADRO

maximum speed (Sm) is 6.2425 km/hour and the current condition is VA = 847.2 smp/hour which experiences a delay of 105 seconds, the queue length (Qm) is 133 meters and the normalization time required is 0.021 seconds, which is much smaller than the green light duration, which is 25 seconds. On Sunday, the maximum volume (Vm) was 801.472 smp/hour, the maximum density (Dm) was 119.946 smp/km, the maximum speed (Sm) was 6.682 km/hour and taking the current condition VA = 733.2 smp/hour which experienced a delay of 105 seconds, the queue length (Qm) was 209 meters and the normalization time required was 0.029 seconds, much smaller than the green light duration, which was 25 seconds. On Monday, the maximum volume (Vm) was 1074.366 smp/hour, the maximum density (Dm) was 162.095 smp/km, the maximum speed (Sm) was 6.628 km/hour and the current condition VA = 806.4 smp/hour which experienced a delay of 105 seconds, the queue length (Qm) was 129 meters and the normalization time required was 0.020 seconds, which was much smaller than the green light duration of 25 seconds, and on Friday, the maximum volume (Vm) was 1072 smp/hour, the maximum density (Dm) was 173.14 smp/km, the maximum speed (Sm) was 6.193 km/hour and the current condition VA = 628.8 smp/hour which experienced a delay of 105 seconds, the queue length (Qm) was 78 meters and the normalization time required was 0.013 seconds, which was much smaller than the green light duration of 25 seconds. is shorter than the green light duration of 25 seconds. This means that when the light changes from green to red, all queuing vehicles have crossed the stop line. It can be seen in Figure 4.20 that the performance of the traffic light compared to the flow condition of VA = 847.2 pcu/hour experienced a queue length of 4300.86 meters and required a normalization time of 9.01 seconds, which is still shorter than the green light duration of 25 seconds. This means that when the light changes from green to red, all queuing vehicles have crossed the stop line.

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