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Application of Compatible Graph and Webster Methods for Traffic Light Arrangement in Jepara

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ABSTRACT

The problem of congestion has become a common problem that is often found on the highways, especially at the crossroads, without exception in Jepara Regency. The Mayong-Jepara Highway intersection is classified as a busy intersection that is full of vehicles during every departure and return hours, which are dominated by factory employees. Congestion often occurs at these intersections even though there are traffic lights that regulate the movement of vehicles. So, This study aims to find the solutions to congestion problems at Mayong-Jepara Highway intersection through compatible graph modeling and optimizing traffic light cycle time using the Webster method. Compatible graphs are used to determine traffic flows that are worked to move simultaneously without causing collisions, and that are used to carry out the graph weighting to determine the number of phases. The variables used in this applied research are the data on the number of vehicles, road width, and traffic light duration that taken directly in the field. Because the traffic density in the morning and afternoon is different for each intersection arm. Thus, the cycle time is determined in 2 sessions namely the morning and the afternoon. From the modeling of the compatible graph that has been weighted, it is obtained that the morning and afternoon sessions have 3 phases as the total which are then used to determine the traffic light cycle time. As a result, the cycle times for the morning session are 98 seconds, and the afternoon session is 155 seconds. The results were then simulated with PTV Vissim software and assessed to be quite effective in dealing with congestion and heavy traffic at the Mayong-Jepara Highway intersection especially in the afternoon session.

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A. INTRODUCTION

Generally, graph theory is widely applied directly to solving real-life problems, both in science and other disciplines (Tanveer, 2017). In mathematics and computer science, graph theory is a study of graphs which are mathematical structures used to model pairwise relations between objects (Elumalai, 2020). A graph is a set of objects in the form of points connected by edges. Graphs are used to model and connect relationships between certain objects, such as in map making, social network analysis, finding shortest paths, and traffic management.

A compatible graph is a graph whose vertices and edges show matching pairs of objects (compatible). In a compatible graph the points represent the objects to be managed (vertex) and the edges represent compatible pairs of objects. The optimal solution to the traffic management problem was found in 1968 by Stoffers through a compatible graph approach that was modeled on traffic flow by finding the most efficient route (Baruah, 2014). Traffic flow from/to a road connected to an intersection represented by a vertex. Vertices in a compatible graph are connected by an edge, if and only if they both flow as representations of these two vertices can move simultaneously without causing an accident (Lusiani et al., 2020).

Congestion is a common problem that is often found on highways, especially at intersections, in the Jepara Regency is no exception. One of the congestion factors is the density estimation of vehicles and traffic management that's not appropriate causing a buildup of vehicles and traffic flow density (Isnaeni et al., 2021). In recent years, the Jepara Regency has experienced rapid economic growth as marked by the establishment of many manufacturing industries. Economic grow and development increase lead to high number of vehicles and trigger traffic congestion (Vidhya & Banu, 2014). The increasing number of vehicles in recent years caused intersection that use the fixed time controller system to lose their effectiveness in managing traffic (Adeke et al., 2018). This makes the traffic light duration has been set by the previous system to be inefficient if applied in the long term, so it need some sessionical evaluations and reset the duration of red, yellow, and green signal (Alkandari et al., 2014), as shown in Figure 1.

Figure 1. The Traffic on the Mayong-Jepara Highway (Author's Observation)

The Mayong-Jepara Highway intersection is located in Mayong Lor village, Mayong subdistrict, Jepara Regency, Central Java. The intersection has 4 branches with different traffic light durations, road width, traffic density, and peak hours in each arm of the intersection. This density usually occurs during work departure and return hours, between 06.00-07.00 WIB and 16.00-17.00 WIB. During work departure hours (morning), the highest vehicle density occurs on Jepara-Kudus Street (east direction) because most of the drivers who are factory employees come from that direction. Meanwhile, during work returns hours (afternoon), the highest vehicle density occurs on Pecangaan-Damaran Street (west direction) due to the location of the factory in the west of the intersection. It is necessary to make arrangements that focus on adjusting the performance of the traffic lights at different times of the day (Wijaya et al., 2019).

Traffic lights are one of the most commonly used traffic control devices at intersections. These lights are used to indicate when the vehicles must stop or move alternately from different directions (Setiawan & Budayasa, 2017). Traffic lights are used at intersections to solve conflict between traffic flows in traffic control problems (Suyudi & Sukono, 2018). Most of the current traffic light settings are still not optimal because at intersections there are traffic lights that do not consider the optimal duration of red and green light time based on vehicle density. This causes the queue of vehicles at the intersection to increase. In addition, long vehicle queues and the mismatches in the duration of red and green lights make drivers run red lights so that they can endanger other drivers. Several studies have tried to find traffic safety solutions through various models (Gao et al., 2018).

One way to solve this problem is by managing traffic through a compatible graph model and the Webster method. Webster method used to determine the time of the traffic light has been developed by F.V. Webster (Prihantini et al., 2020). Webster's method is traffic light design with an analytical approach of determining the optimum cycle time (C_0) that corresponds to minimum total delay of vehicles at the intersection (Kumar & Prasad, 2020). The compatible graph model is used to determine which flows are allowed to run simultaneously without causing conflict and the Webster method is used to determine the optimum cycle time. The main advantage of the Webster method is the simplicity of the implementation in real life (Ali et al., 2021). The Webster method considers reducing the duration of the red light and increasing the duration of the green light in cases of high vehicle volume.

Some research about traffic management using the Webster method has been carried out, such as (Wijaya et al., 2019) on analyzing the waiting time at the Yogjakarta Mirota Kampus intersection; Singh (2022) on repairing a signalized intersection in Bengaluru; Reddy and Reddy (2016) on design signal at T-intersection in Nandyal town; and Li et al. (2021) to optimal transportation design with signal control at the intersection. There are also research on traffic management using compatible graph such as Sikar and Aslan (2022) on delay calculation of autonomous vehicles at signalized intersections; Sarbaini (2022) on modeling traffic flow at intersections in the Pekanbaru City.

This research aims to solve the problem of congestion at the Mayong-Jepara Highway intersection through the application of compatible graph and Webster Method. The output obtained is in the form of traffic flow modeling which is used as a reference for drivers and the optimal traffic light cycle time at the intersection. The results of this research are expected to be a solution and reference for authorities, in this case the Department of Transportation of the Jepara Regency in regulating the optimal duration of traffic light to reduce congestion.

B. METHODS

The type of research used in this research is applied research with a quantitative approach in the case of traffic management at the Mayong-Jepara Highway intersection in the Jepara Regency. The research time took place in March-May 2023. The data needed are traffic conditions and road geometry, data on the number of vehicles, road width, and duration of traffic lights taken directly in the field and through secondary data. The research procedure is as follows:

1. Data collection include geometry intersection, vehicle volume, road width, and traffic light duration.
2. Drawing the intersection of the Mayong-Jepara Highway and its traffic flow.
3. Modeling the intersection into a compatible graph where the vertices on the graph represent the flow of traffic on each intersection path while the edges on the graph represent pairs of flows that when moving together do not cause accidents (compatible).
4. Simplify compatible graph and convert it into a weighted graph. As for each weighting follows the following conditions.

a. Weighted value based on road width: (1) Road width less than 3 meters is given a weight 4; (2) Road width 3 to 4 meters given is a weight 3; (3) Road width more than 4 to 5 meters is given a weight 2; and (4) Road width more than 5 meters is given a weight 1.
b. Weighted value based on vehicle volume: (1) Vehicle volume above 2,000 vehicles/hour is given a weight 5; (2) Vehicle volume of 1,500-1,999 vehicles/hour is given a weight 4; (3) Vehicle volume of 1,000-1,499 vehicles/hour is given a weight 3; (4) Vehicle volume of 500-999 vehicles/hour is given a weight 2; dan (5) Vehicle volume from 0-499 vehicles/hour is given a weight 1.

5. Calculate time using the Webster method includes the optimum cycle time, effective green time, and red time.
6. Represent the calculation results that have been obtained, as shown in Figure 2.

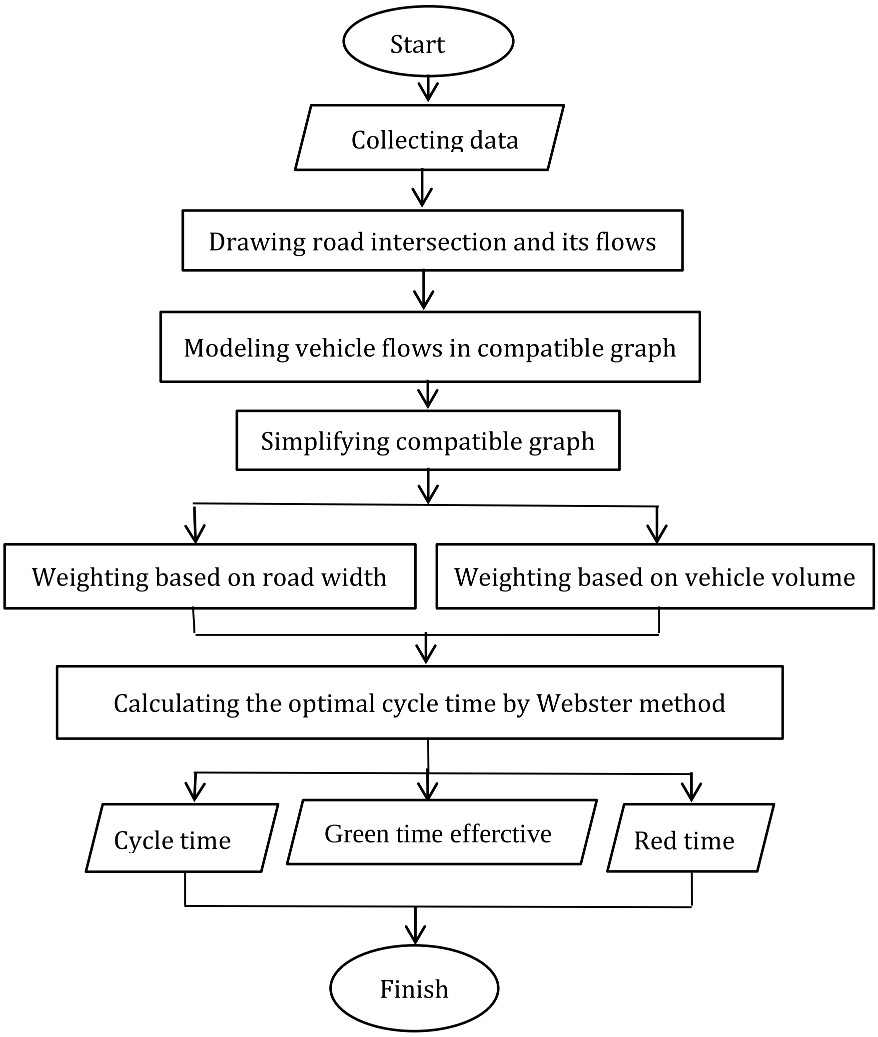

Figure 2. Research Flow Scheme

C. RESULT AND DISCUSSION

1. Data Research

The data needed in this study are road geometry data, road width, number of vehicles, and the duration of traffic lights, as shown in Figure 3.

Figure 3. Mayong-Jepara Highway Intersection (Google Maps)

The width of the path at the Mayong-Jepara Highway intersection is as follows:

a. Mayong-Jepara Street has 2 paths, the width of each entry and exit path is 4,5 meters.
b. Jepara-Kudus Street has 2 paths, the entrance path has a width 5 meters and the width of the exit path has a width 6 meters.
c. Mayong-Pancur Street has 2 paths, the width of each entry and exit path 4 meters.
d. Pecangaan-Damaran Street has 2 paths, the entrance path has a width 6 meters and the exit path has a width 5 meters. The following data on traffic light timing at the Mayong-Jepara Highway Intersection, as shown in Table 1.

Table 1. Traffic Light Timing Data at the Mayong-Jepara Highway Intersection (Author's Observation)

Road Section	Red (seconds)	Yellow (seconds)	Hijau (seconds)	Total Time
Mayong-Jepara	80	3	15	98
Jepara-Kudus	55	3	40	98
Mayong-Pancur	80	3	15	98
Pecangaan-Damaran	80	3	15	98

Data collection on the number of vehicles passing at the Mayong-Jepara Highway intersection was carried out in 3 days, namely Sunday, 14 May 2023, Monday, 15 May 2023, and Friday 19 May 2023 in three times including morning (06.00-07.00), noon (12.00-13.00), and afternoon (16.00-17.00). The data used is data on the number of vehicles on Monday, 15 May 2023 (peak day) in 2 sessions, namely morning and afternoon, as shown in Table 2.

Table 2. Traffic Light Timing Data at the Mayong-Jepara Highway Intersection (Author's Observation)

Road	Units	Time		
Section		06.00-07.00	12.00-13.00	16.00-17.00
Mayong- Jepara	vehicle/hour	1339	939	1057
	pcu/hour	379	325,8	346,9
Jepara- Kudus	vehicle/hour	4619	1522	2219
	pcu/hour	1121,3	752	755,6
Mayong- Pancur	vehicle/hour	911	737	931
	pcu/hour	258,9	256	331,9
Pecangaan- Damaran	vehicle/hour	2032	1432	4352
	pcu/hour	638,4	599,8	1157

2. Data Processing

The traffic flow system at the Mayong-Jepara Highway intersection is described as shown in Figure 4.

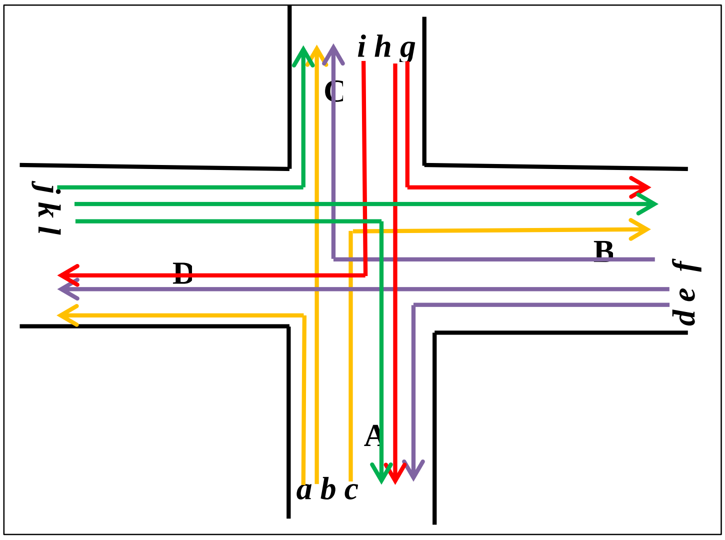

Figure 4. Traffic Flow Scheme

Description:
A = Mayong-Jepara Street.
B = Jepara-Kudus Street.
C = Mayong-Pancur Street.
D = Pecangaan-Damaran Street.
→ = vehicle flow from Mayong-Jepara Street.
→ = vehicle flow from Jepara-Kudus Street.
→ = vehicle flow from Mayong-Pancur Street.
→ = vehicle flow from Pecangaan-Damaran Street.

From the traffic flow scheme in Figure 4, compatible and incompatible traffic flows can be identified. Two traffic flows are said to be compatible if the two flows can run simultaneously without conflict. The identification of traffic flows at the Mayong-Jepara Highway intersection is in Table 3.

Table 3. Compatible and Incompatible Flows

Flow	Compatible With	Not Compatible with
a	*b, c, d, e, f, g ,h ,i, j, k, l*	-
b	*a, c, d, f, g, h, j*	*e, i, k, l*
c	*a, b, d, g, j, k*	*e, f, h, i, l*
d	*a, b, c, e, f, g, h, i, j, k, l*	-
e	*a, d, f, g, i, j, k*	*b, c, h, l*
f	*a, b, d, e, g, j*	*c, h, i, k, l*
g	*a, b, c, d, e, f, h, i, j, k, l*	-
h	*a, b, d, g, i, j, l*	*c, e, f, k*
i	*a, c, d, g, h, j*	*b, e, f, k, l*
j	*a, b, c, d, e, f, g, h, i, k, l*	-
k	*a, c, d, e, g, j, l*	*b, f, h, i*
l	*a, d, g, h, j, k*	*b, c, e, f, i*

Identification of traffic flows in Table 3 is converted into a compatible graph modeling as shown in Figure 5.

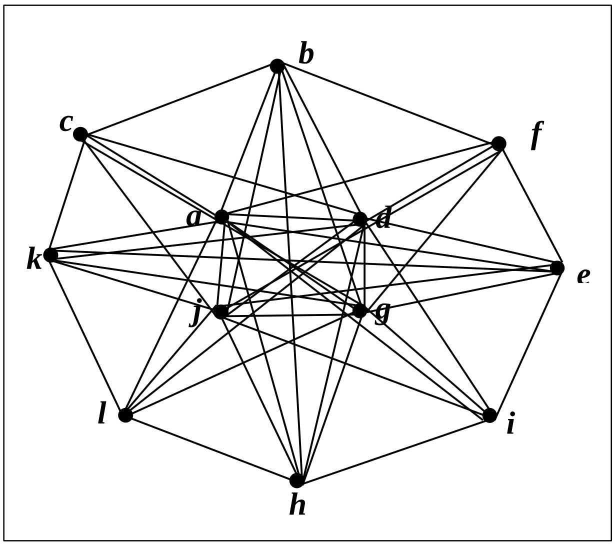

Figure 5. Flow Modeling at Mayong-Jepara Highway Intersection with Compatible Graph

The compatible graph in Figure 5 is simplified by eliminating the vertices *a*, *d*, *g*, and *j* and their connecting edges because the flows *a*, *d*, *g*, and *j* are compatible to all flows in each intersection path. Next, a simpliefied compatible graph is weighted based on the assumptions that have been determined. The weighting of road traffic conditions in the morning and afternoon sessions is described as follows.

a. Vertices of *b* and *c* (traffic flow at the Mayong-Jepara Street) have an exit width of 4,5 meters and experience peak vehicle volume in the morning at 06.00-07.00 with a total of 1.339 vehicles/hour while in the afternoon at 16.00-17.00 vehicles passing as many as 1.057 vehicles/hour. The width of the road is given a value of 2 and the volume of vehicles is given a weight of 3, so in the morning and afternoon sessions the *b* and *c* vertices each have a value of 5. So the *bc* edge is given a weight of 10.

b. Vertices of *e* and *f* (traffic flow at the Jepara-Kudus Street) have an exit width of 6 meters and experience peak vehicle volume in the morning at 06.00-07.00 with a total of 4.619 vehicles/hour while in the afternoon at 16.00-17.00 vehicles passing as many as 2.219 vehicles/hour. The width of the road is given a value of 1 and the volume of vehicles is given a weight of 5, so in the morning and afternoon sessions the *e* and *f* vertices each have a value of 6. So the *ef* edge is given a weight of 12.
c. Vertices of *h* and *i* (traffic flow at the Mayong-Pancur Street) have an exit width of 4 meters and the volume of vehicles in the morning at 06.00-07.00 is 911 vehicles/hour while the peak hour of vehicles occurs in the afternoon at 16.00-17.00 with the number of vehicles 931 vehicles/hour. The width of the road is given a weight of 3 and the volume of vehicles is given a weight of 2, so in the morning and afternoon sessions the *h* and *i* vertices each have a value of 5. So the *hi* edge is given a weight of 10.
d. Vertices of *k* and *l* (traffic flow at the Damaran-Pecangaan Street) have an exit width of 5 meters and the volume of vehicles in the morning at 06.00-07.00 is 2.032 vehicles/hour while the peak hour of vehicles occurs in the afternoon at 16.00-17.00 with the number of vehicles 4.352 vehicles/hour. The width of the road is given a value of 2 and the volume of vehicles is given a weight of 5, so in the morning and afternoon sessions *k* and *l* vertices have a weight of 7 each. So the *kl* edge is given a weight of 14. Graph simplification and weighting is shown in Figure 6.

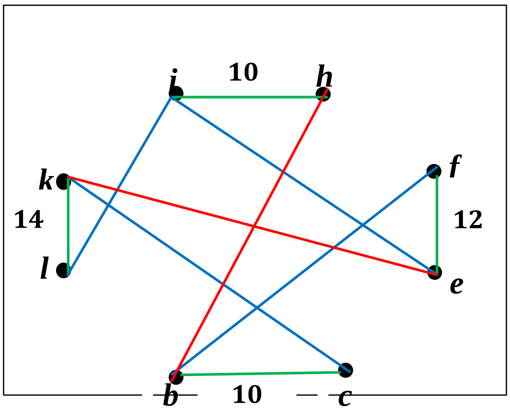

Figure 6. Simplification and Weighting of Compatible Graph

Description:
a. The green-colored side shows two currents moving simultaneously.
b. The blue-colored side shows two currents going in the same direction.
c. The red-colored side shows two currents running in opposite directions.

Based on Figure 6, the same weighting results were obtained in the morning and afternoon sessions. The Mayong-Jepara Street and the Mayong-Pancur Street weights 10, the Jepara-Kudus Street weights 12, and the Pecangaan-Damaran Street weights 14. The weighting results in 3 phases which will be used to determine the optimum cycle time. The following is the determination of the optimum cycle time using the Webster method in the morning and afternoon sessions, as shown in Table 4.

Table 4. Calculating the optimal cycle time by Webster method

Calculation on Cycle Time for Morning Session	**Calculation on Cycle Time for Afternoon Session**
Lost time (R) = 5 seconds	Lost time (R) = 5 seconds
Traffic flow at each intersection a. The Mayong-Jepara Street $y_A = \frac{q_A}{s_A} = \frac{379}{2.175} = 0{,}1743$ b. The Jepara-Kudus Street $y_B = \frac{q_B}{s_B} = \frac{1.121{,}3}{3.150} = 0{,}3560$ c. The Mayong-Pancur Street: $y_C = \frac{q_c}{s_c} = \frac{258{,}9}{1.975} = 0{,}1311$ d. The Damaran-Pecangaan Street $y_D = \frac{q_D}{s_D} = \frac{638{,}4}{2.550} = 0{,}2504$ $Y = \sum y_{max} = 0{,}1743 + 0{,}3560 + 0{,}2504 = 0{,}7806$	Traffic flow at each intersection a. The Mayong-Jepara Street $y_A = \frac{q_A}{s_A} = \frac{346{,}9}{2.175} = 0{,}1595$ b. The Jepara-Kudus Street $y_B = \frac{q_B}{s_B} = \frac{755{,}6}{3.150} = 0{,}2399$ c. The Mayong-Pancur Street $y_C = \frac{q_c}{s_c} = \frac{331{,}9}{1.975} = 0{,}1681$ d. The Damaran-Pecangaan Street $y_D = \frac{q_D}{s_D} = \frac{1.157}{2.550} = 0{,}4537$ $Y = \sum y_{max} = 0{,}1681 + 0{,}2399 + 0{,}4537 = 0{,}8616$
Total lost time (L) $L = 2n + R = 2(3) + 5 = 11$ seconds	Total lost time (L) $L = 2n + R = 2(3) + 5 = 11$ seconds
Optimum cycle time $C_0 = \frac{1{,}5\times L+5}{1-Y} = \frac{1{,}5\times 11+5}{1-0{,}7806} = 97{,}9829 \approx 98$ seconds	Optimum cycle time $C_0 = \frac{1{,}5\times L+5}{1-Y} = \frac{1{,}5\times 11+5}{1-0{,}8616} = 155{,}402 \approx 155$ seconds
Effective green time in each phase $g = \frac{y(C_0 - L)}{Y}$ a. Effective green time of phase A (the Mayong-Jepara Street and the Mayong-Pancur Street) $g_A = \frac{0{,}1743(98-11)}{0{,}7806} = 19{,}42 \approx 19$ seconds b. Effective green time of phase B (the Jepara-Kudus Street) $g_B = \frac{0{,}3560(98-11)}{0{,}7806} = 39{,}67 \approx 40$ seconds c. Effective green time of phase C (the Damaran-Pecangaan Street) $g_C = \frac{0{,}2504(98-11)}{0{,}7806} = 27{,}90 \approx 28$ seconds	Effective green time in each phase $g = \frac{y(C_0 - L)}{Y}$ a. Effective green time of phase A (the Mayong-Jepara Street and the Mayong-Pancur Street) $g_A = \frac{0{,}1681(155-11)}{0{,}8616} = 28{,}16 \approx 28$ seconds b. Effective green time of phase B (the Jepara-Kudus Street) $g_B = \frac{0{,}2399(155-11)}{0{,}8616} = 40{,}20 \approx 40$ seconds c. Effective green time of phase C (Damaran-Pecangaan Street) $g_C = \frac{0{,}4537(155-11)}{0{,}8616} = 76{,}04 \approx 76$ seconds
Effective red time in each phase $red\ time = C_0 - green\ time - yellow\ time$ a. Red time of phase A (the Mayong-Jepara Street and th Mayong-Pancur Street) $red\ time_{phase\ A} = 98 - 19 - 5 = 74$ seconds b. Red time of phase B (the Jepara-Kudus Street) $red\ time_{phase\ B} = 98 - 40 - 5 = 53$ seconds c. Red time of phase C (the Jepara-Kudus Street) $red\ time_{phase\ C} = 98 - 28 - 5 = 65$ seconds	Effective red time in each phase $red\ time = C_0 - green\ time - yellow\ time$ a. Red time phase A (the Mayong-Jepara Street and the Mayong-Pancur Street) $red\ time_{fase\ A} = 155 - 28 - 5 = 122$ seconds b. Red time phase B (the Jepara-Kudus Street) $red\ time_{fase\ B} = 155 - 40 - 5 = 110$ seconds c. Red time phase C (the Damaran-Pecangaan Street) $red\ time_{fase\ C} = 155 - 76 - 5 = 74$ seconds

Sadturation flow at each intersection segment. The standard values for saturation flow based on the lane width by Webster are given as in Table 5.

Table 5. Saturation Flow Values (Reddy & Reddy, 2016)

Width (m)	**3**	**3,5**	**4**	**4,5**	**5**	**5,5**
Saturation flow (s) (pcu/hour)	1.850	1.875	1.975	2.175	2.550	2.900

If the lane width more than 5,5 meters, so saturation flow is calculated by this formula.

$$s = 525 \times lane\ width\ (pcu/hour)$$

Saturation flow at each intersection segment:

a. The Mayong-Jepara Street: $s_A = 2.175$ pcu/hour
b. The Jepara-Kudus Street: $s_B = 6 \times 525 = 3.150$ pcu/hour
c. The Mayong-Pancur Street: $s_C = 1.975$ pcu/hour
d. The Pecangaan-Damaran Street: $s_D = 2550$ pcu/hour

3. Results

Based on the results of the cycle time calculation using the Webster method, the new cycle time results are shown in Table 6 and Table 7.

Table 6. Traffic Light Duration in the Morning Session by Webster Method

Road Section	Red (seconds)	Yellow (seconds)	Green (seconds)	Total Time
Mayong-Jepara St.	74	5	19	98
Jepara-Kudus St.	53	5	40	98
Mayong-Pancur St.	74	5	19	98
Pecangaan-Damaran St.	65	5	28	98

Table 7. Traffic Light Duration in the Afternoon Session by Webster Method

Road Section	Red (seconds)	Yellow (seconds)	Green (seconds)	Total Time
Mayong-Jepara St.	112	5	28	155
Jepara-Kudus St.	110	5	40	155
Mayong-Pancur St.	122	5	28	155
Pecangaan-Damaran St.	74	5	76	155

Based on Table 6, in the morning session, the optimum cycle time was obtained by the Webster method of 98 seconds, the same as the previous cycle time. However, there was an increase in the duration of the green light and a reduction in the duration of the red light at the intersection of Mayong-Jepara Street, Mayong-Pancur Street and Pecangaan-Damaran Street. The Jepara-Kudus Street intersection has the longest green light duration because it is the most heavily traveled in the morning departure hours.

Based on Table 7, in the afternoon session, the optimum cycle time was obtained using the Webster method of 155 seconds, 57 seconds longer than the previous cycle time. This occurs because the total number of vehicles passing through all sections of the intersection peaks in the afternoon at work return hours, namely 16.00-17.00 WIB. Due to the considerable increase in cycle time, which increased by 57 seconds, there was also an increase in the duration of the red and green lights at each intersection. The intersection of Pecangaan-Damaran Street has the longest green light duration because this section is the most congested for vehicles to pass from work in the afternoon.

The results of this cycle time research were simulated through the software of traffic engineering PTV Vissim. From the results of the simulation it can be seen that the cycle time generated by the Webster method is sufficiently effective to overcome congestion and traffic congestion on the Mayong-Jepara Highway intersection especially in the afternoon. Although the intersection of Pecangaan-Damaran Street has a relatively long cycle time and red light duration than ever before, the queue of vehicles from the road section can come out and run smoothly because it is offset by long green light duration.

D. CONCLUSION AND SUGGESTIONS

The application of graph theory is used to model the traffic flow at the Mayong-Jepara Highway intersection through a compatible graph. The compatible graph modeling is then simplified and given a weight that will be used to determine the number of phases in the traffic light cycle time at that intersection. The result obtained is 3 phases. Optimization of the traffic light cycle time with the Webster Method is made into two sessions, namely morning and afternoon. The cycle time obtained in the morning session is 98 seconds. The Mayong-Jepara Street and the Mayong-Pancur Street produce a green light for 19 seconds, yellow for 5 seconds, and red for 74 seconds. The Jepara-Kudus Street produces a green light for 40 seconds, yellow for 5 seconds, and red for 53 seconds. The Pecangaan-Damaran Street produces a green light for 28 seconds, yellow for 5 seconds, and red for 65 seconds.

During the afternoon session, there was a significant addition of the cycle time, which was originally 98 seconds to 155 seconds. This happens because the total number of vehicles passing in all sections of the intersection experiences its peak in the afternoon at work return hours, namely 16.00-17.00 WIB. Mayong-Jepara Street and Mayong-Pancur Street produces a green lights for 28 seconds, yellow for 5 seconds, and red for 112 seconds. The Jepara-Kudus Street produces a green lights for 40 seconds, yellow for 5 seconds, and red for 110 seconds. The Pecangaan-Damaran Street produces a green light of 76 seconds, yellow for 5 seconds, and red for 74 seconds. The results of this research can be used as consideration for the Jepara Transportation Department to overcome congestion problems.

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