Optimizing Traffic Light Timing Using Graph Theory: A Case Study at Urban Intersections

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ABSTRACT

Purpose of the study: This study aims to optimize traffic light timing at the Usman Salengke-Poros Malino-K.H. Wahid Hasyim intersection using a graph theory approach. By modeling compatible traffic flows and calculating optimal signal durations, the study seeks to reduce congestion, minimize delays, and improve traffic efficiency.

Methodology: This study utilized manual traffic volume data collection methods with direct field observations at the Usman Salengke-Poros Malino-K.H. Wahid Hasyim intersection. It employed Webster's method for optimal cycle calculation and MATLAB software for simulation. Tools included measuring tapes (Stanley), stopwatches (Casio), and data sheets for recording traffic flow. Surveys captured vehicle types and peak hour volumes.

Main Findings: The optimal traffic light cycle duration was calculated as 95 seconds, reducing the original cycle time of 128 seconds. Peak traffic volume was observed at 1,383 pcu/hour (Usman Salengke North). The green light duration increased for Usman Salengke North to 39 seconds and for Poros Malino to 28 seconds. Total average vehicle waiting time decreased by 33.3%, with improved throughput by 20%.

Novelty/Originality of this study: This study introduces a practical application of graph theory for optimizing traffic light timing, using compatible flow modeling to simplify intersection analysis. Unlike adaptive systems requiring expensive technology, this approach relies on manual traffic data, offering cost-effective solutions. It advances existing knowledge by providing a simplified, scalable method for reducing congestion and enhancing traffic efficiency in urban settings.

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1. INTRODUCTION

Graph theory is a branch of discrete mathematics that has long been known for its wide application in various fields, including traffic system management. Graphs model discrete objects and relationships between objects using points and lines as visual representations [1]-[3]. One concrete application of graph theory is in the arrangement of traffic lights at intersections, which aims to manage vehicle flow efficiently and prevent congestion [4]-[6]. Intersections such as Usman Salengke and Poros Malino Streetsoften experience congestion due to suboptimal traffic light duration. Therefore, this study uses graph theory and the Webster method to find a solution for better traffic light duration management.

Traffic congestion at intersections not only hinders mobility but also poses a risk of accidents [7]-[9]. Traffic flow conflicts, especially at busy intersections, are one of the main causes of congestion [10]-[12]. To overcome this problem, compatibility graph theory is applied to model traffic flows that can run simultaneously without causing conflict [13]-[15]. This approach allows for more efficient traffic light management, thereby minimizing vehicle queues and waiting times that are often complained about by road users.

Adaptive traffic light systems have become a solution in various developed countries, where the duration of red and green lights is set based on vehicle density. This system ensures that vehicle flows from various directions have a more balanced waiting time, reducing congestion, and increasing traffic efficiency [16]-[18]. However, the implementation of adaptive systems requires accurate real-time data and integration between intersections [19], [20]. In this study, graph theory is used to model a single intersection with a simpler yet effective approach in calculating the optimal duration of traffic lights [21]-[23].

Compatibility graph theory offers a practical method for managing traffic lights by modeling vehicle flows as nodes and compatibility relationships between flows as edges [24], [25]. This approach helps identify traffic flows that can move together without causing conflict, thus minimizing the risk of congestion [26]-[28]. Using the Webster method, this study calculates the optimal duration of green, yellow, and red lights based on vehicle volume data and road geometry [29]-[31]. The results of this approach are expected to improve the smoothness of traffic flow at the intersections that are the focus of the study.

Graph theory is a branch of discrete mathematics that has long been known for its wide application in various fields, including traffic system management. Graphs model discrete objects and relationships between objects using points and lines as visual representations [32], [33]. One concrete application of graph theory is in the arrangement of traffic lights at intersections, which aims to manage vehicle flow efficiently and prevent congestion [34], [35]. Intersections such as Usman Salengke and Poros Malino Streetsoften experience congestion due to suboptimal traffic light duration.

Therefore, this study uses graph theory and the Webster method to find a solution for better traffic light duration management. Traffic congestion at intersections not only hinders mobility but also poses a risk of accidents [36]-[38]. Traffic flow conflicts, especially at busy intersections, are one of the main causes of congestion [39]. To overcome this problem, compatibility graph theory is applied to model traffic flows that can run simultaneously without causing conflict. This approach allows for more efficient traffic light management, thereby minimizing vehicle queues and waiting times that are often complained about by road users.

Previous research has conducted research that focuses on the problem of congestion at the Street Kolonel Yos Sudarso intersection due to the duration of the green light being shorter than the red light, so that the vehicle waiting time is not optimal [40]. Then previous research used the Monte Carlo simulation method to determine the optimal time for traffic lights, with a probability distribution-based approach that focuses on the arrival time and movement of vehicles in each direction [41]. This approach is effective in generating optimal time estimates, but it lacks consideration of the interactions between compatible traffic flows in each direction. The main gap lies in the method used, where the current study introduces a practical application of graph theory to simplify intersection analysis and improve traffic efficiency, which has not been discussed in depth in previous studies. The novelty of this research is the use of cross graph theory combined with Webster's method to optimize the timing of traffic lights at urban intersections. This approach offers a more systematic, simpler, and cheaper assessment compared to high-tech adaptive systems, while filling the gap in previous research with more structured and accurate data analysis.

This shows the importance of the current study to offer a more affordable solution that can be widely applied in various urban conditions. In contrast, the current study uses a graph theory approach to analyze compatible traffic flows, supported by the Webster method for optimal cycle calculation and simulation using MATLAB. This approach is more structured and analytical than probabilistic, allowing for a more comprehensive analysis of traffic efficiency at intersections. Thus, the current study fills the gap of previous studies by offering a more systematic, simple, and scalable method to optimize traffic light timing, especially in urban areas with limited adaptive technology. This makes this study important to be conducted in order to provide a more effective and affordable solution to reduce congestion and improve traffic efficiency..

Adaptive traffic light systems have become a solution in various developed countries, where the duration of red and green lights is set based on vehicle density. This system ensures that vehicle flows from various directions have a more balanced waiting time, reducing congestion, and increasing traffic efficiency. However, the implementation of adaptive systems requires accurate real-time data and integration between intersections. In this study, graph theory is used to model a single intersection with a simpler yet effective approach in calculating the optimal duration of traffic lights. Compatibility graph theory offers a practical method for managing traffic lights by modeling vehicle flows as nodes and compatibility relationships between flows as edges. This approach helps identify traffic flows that can move together without causing conflict, thus minimizing the risk of congestion. Using the Webster method, this study calculates the optimal duration of green, yellow, and red lights based on vehicle volume data and road geometry. The results of this approach are expected to improve the smoothness of traffic flow at the intersections that are the focus of the study.

2. THEORETICAL BASIS

Graphs are used to describe various existing structures, such as organizational structures, road routes, and course flowcharts [40]-[42]. The goal is to describe objects so that they are easier to understand. A graph G consists of; A graph consists of two finite sets, namely the set of non-empty vertices V(G) and the set of edges E(G) [45]. Each edge is associated with one or two points. An edge associated with one point is called a Loop.

Traffic signal optimization is an important step in reducing congestion at intersections [46], [47]. This study uses graph theory as a basis for representing the relationship between traffic flows at an intersection. The graph consists of $G\ (V, E)$ on the node (V) which represents objects (e.g. lanes or traffic directions) and edges (E) which represent relationships between nodes (e.g. traffic flow compatibility). A visual representation of the graph is shown in Figure 1 below.

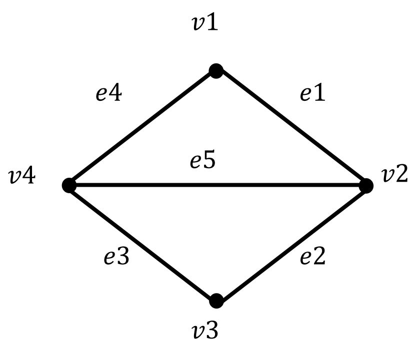

Figure 1. A graph

The Compatibility Graph is used to show compatible pairs of traffic flows (can move together without causing conflict) [48], [49], [50]. An example of a compatibility graph is shown in Figure 2, where nodes represent traffic directions and edges connect compatible flows. Nodes a, b, c and others represent traffic flows. Edges connect nodes whose flows can move together.

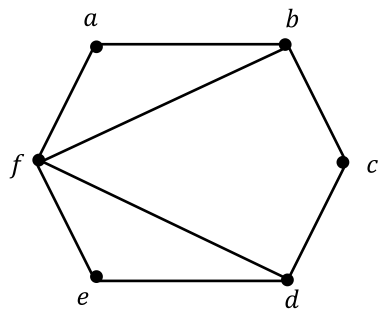

Figure 2. Compatible graph form

Webster's method is used to determine the optimal traffic light switching time. The formula used to calculate the optimal cycle length is:

$$C = \frac{1.5L+5}{1-Y} \qquad ...(1)$$

Where:
C: Traffic light cycle length (seconds)
L: Total time lost (seconds)
L: The sum of the critical current ratios of all phases.

Table 1 below explains the saturation flow based on road width, which is used for the calculation..

Table 1. Saturation current at the junction (Webster method)

Road width (m)	3.05	3.35	3.65	3.95	4.25	4.60	4.90	5.20
Saturation current (pcu/h)	1850	1875	1900	1950	2075	2250	2475	2700

Source: Lecture Dictation 9 RLL, ITP teaching staff

If the width (l) exceeds this, then the saturation flow = l × 525 (pcu/h). Figure 3 below shows a traffic flow diagram at a road intersection, which is the basis for modeling in this method.

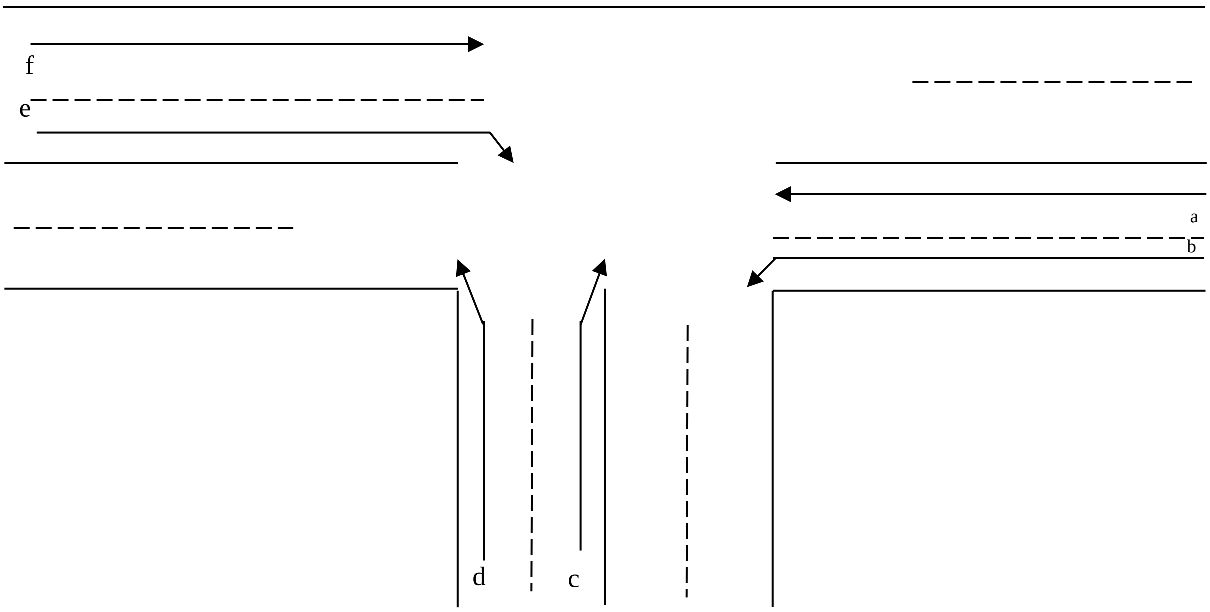

Figure 3. Traffic flow diagram at a road intersection

Information:
– – – – – – – – – – – – – – = traffic flow
⟶ = connecting compatible pairs of dots

The explanation of Figure 3 is that current a is compatible with currents b, d and f, but not with c, and e. While current f is compatible with currents a, b, c, d, and e. This compatibility can be shown with a compatible graph, namely the vertices represent traffic flows and the edges connect pairs of vertices whose currents are compatible.

Traffic lights are a control device using lights installed at intersections with the aim of using lights installed at intersections with the aim of regulating traffic flow [51], [52]. Traffic flow regulation at intersections is basically intended for how vehicle movements in each group of vehicle movements can move alternately so as not to interfere with each other between existing flows. There are various types of control using traffic lights where these considerations are highly dependent on the situation and conditions of the existing intersection such as volume, geometry, intersections and so on.

Geometry and traffic conditions will affect the capacity and performance of traffic at intersections [53], [54]. Therefore, planning must be able to design in such a way that it is able to distribute time to each group of vehicle movements proportionally so as to provide the best possible performance. The traffic light system uses the following types of lights [55], [56]:

a. Green light; is a vehicle that gets a signal must move forward.
b. Yellow light; is a vehicle that gets a signal must anticipate if possible to make a decision for the next traffic light to come into effect (green or red light).

c. Red light; is a vehicle that gets a signal must stop before the stop line.

Please note that with the new traffic light regulations for vehicles turning left as long as it is not specifically regulated, the vehicle may continue turning. The lighting with various lights is applied to separate the traffic light based on time.

3. RESEARCH METHOD

3.1 Types of research

The type of research used in this study is applied, namely one type of research that aims to determine the arrangement of traffic lights at the Usman Salengke-K. H. W. Hasyim-Malino Poros intersection, Gowa Regency. Applied research is a type of research that aims to solve practical problems by applying existing theories or principles in a specific context. Unlike basic research that focuses on developing new theories and knowledge without directly considering practical applications, applied research is more directed at finding solutions that can be used in real-world situations.

3.2 Data source

The data used in this study is primary data. Primary data is data obtained from direct observation in the field. The data to be taken in such a way that each object of research from the population has an equal opportunity to be selected. The population object of this study is the number of vehicles and the number of lanes at the intersection of the Usman Salengke- K. H. W Hasyim- Poros Malino road, Gowa Regency.

3.3 Location and Time of Research

The research location is the Usman Salengke-K. H. Wahid Hasyim-Malino Poros intersection, Gowa Regency, the research period started from August to October.

3.4 Research Procedures

The steps to achieve the objectives of this study begin with data collection. The data collected in this study include two main aspects, namely road geometry data and traffic volume data. Geometry data includes road names and road widths in each section that is part of the intersection. Meanwhile, traffic volume data is recorded in detail with a recording procedure every 15 minutes for a one-hour period during peak hours, which is then converted to units per hour for analysis purposes. The composition of the observed traffic movements consists of three categories, namely: light vehicles (Light Vehicle or LV), including passenger cars, oplets, microbuses, and pick-ups; heavy vehicles (Heavy Vehicle or HV), namely vehicles with more than four wheels; and two- or three-wheeled motorized vehicles (Motor Cycle or MC), such as motorcycles and motorized pedicabs. Data collection was carried out at three different time periods to reflect variations in daily activities. The morning period was carried out at 07.00-08.00 CIT, assuming high mobility of workers and students who depart at that time. The daytime period is carried out at 12.30-1.30 pm CIT, assuming that many students are returning from school and other activities are taking place. Meanwhile, the afternoon period is carried out at 4.30-5.30 pm CIT, assuming the high mobility of workers returning from work. Next, draw the shape of the intersection.

To change the shape of the intersection into a compatible graph, the following steps are taken: First, create nodes on the graph, where each node represents the traffic flow at the intersection. Next, determine the edges that connect the two nodes. This edge is given to represent the relationship between two flows that cross or cross each other, indicating a compatible flow pair [57]. Thus, this compatible graph illustrates how compatible traffic flows can move together without conflict at the intersection. Then simplify the compatible graph, then simplify the compatible graph. The compatible graph is transformed into a weighted directed dual graph by giving weights based on two main parameters [58]:

Road Width:
a. For roads with a width of less than 4 meters, a value of 4 is given.
b. For road widths between 4-5 meters, given a value of 3.
c. For road widths of more than 5 to 6 meters, given a value of 2.
d. For road widths of more than 6 meters, given a value of 1.

Volume of Vehicles:
a. Above 2000 vehicles/hour, given a value of 5.
b. For volumes of 1500-2000 vehicles/hour, given a value of 4.
c. For volumes of 1000-1499 vehicles/hour, given a value of 3.
d. For volumes of 500-998 vehicles/hour, given a value of 2.
e. For volumes of 0-499 vehicles/hour, given a value of 1.

Next, determine the optimum cycle time using the formula:

$$C_0 = \frac{1.5 \times Lt + 5}{1 - FR} \quad ...(2)$$

Determine the maximum number of green time cycles, the number of green time cycles = C_0-Lt
Continued by determining the green time for phases 1, 2, and 3

$$Fase_n = \frac{y_{\max n} \times maximum\ number\ of\ green\ time\ cycles}{FR} \quad ...(3)$$

Red time for phases 1, 2, and 3

$$Fase_n = C_0 - green\ time - yellow\ time \quad ...(4)$$

4. RESULTS AND DISCUSSION

The intersection used as the research location is in Sungguminasa, Gowa Regency. The intersection in question is the intersection of Usman Salengke (south), Malino Poros, Usman Salengke Utara and K.H. Wahid Hasyim. The geometric picture of the intersection can be seen in the image below.

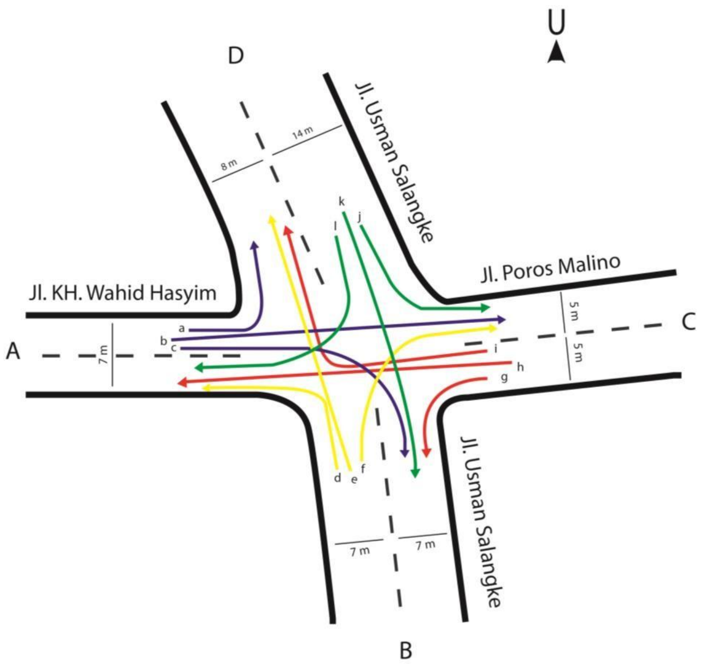

Figure 4. Crossroads

In Figure 4, the northern part is Usman Salengke Streetwhich has two lanes with each entrance and exit lane being 8 meters wide. In addition, there is a left turn lane directly at the entrance lane with a width of 6 meters. The southern part is also Street Usman Salengke, which has two lanes with each entrance and exit lane being 7 meters wide. The western part is Street K.H. Wahid Hasyim, which has two lanes with each entrance and exit lane being 3.5 meters wide. Meanwhile, the eastern part is Street Poros Malino, which also has two lanes with each entrance and exit lane being 5 meters wide. The data on the duration of the traffic light cycle at the four-way intersection of St. Usman Salengke-Poros Malino-K.H.Wahid Hasyim is presented in the following table 2:

Table 2. Traffic light cycle time

Road Section	Red (seconds)	Yellow (seconds)	Green (seconds)
Usman Salengke (south)	81	5	17
Malino Axis	90	5	33
Usman Salengke (north)	72	5	48
K.H. Wahid Hasyim	90	5	33

Based on Table 2, the data on the traffic light cycle at the intersection of St. Usman Salengke-Poros Malino-K.H.Wahid Hasyim, uses 3 phases, where for Usman Salengke Street(south) the red duration is 81 seconds, yellow is 5 seconds and green is 17 seconds. For Street Poros Malino and Street K.H.Wahid Hasyim the red duration is 90 seconds, yellow is 5 seconds and green is 33 seconds. For Usman Salengke Street(north) the red duration is 72 seconds, yellow is 5 seconds and green is 48 seconds. The intersection of Usman Salengke StreetPoros Malino-K.H.Wahid Hasyim is an intersection that often experiences congestion, this is due to the high volume of vehicles. Traffic volume data was obtained by conducting a survey and recording all types of vehicles passing through the intersection.

The traffic volume recorder for 15 minutes every hour, which is then converted from vehicles per hour to passenger car units (pcu) per hour. Traffic flow data collection was carried out for three days, namely Monday, October 7, 2024, representing effective working days; and Sunday, October 20, 2024 representing holiday activities (off peak). From the two days of observations in the field, the peak flow was obtained, namely on Monday, October 7, 2024, which became the traffic volume and composition data in this study. The following data is the result of observations of traffic volume at peak flow which can be seen in the table below.

Table 3. Traffic volume on the Usman Salengke road section (South)

time	(LV) PCE = 1.0		(HV) PCE = 1.3		(MC) PCE = 0.2		Total	
	Vehicles	PCU	Vehicles	PCU	Vehicles	PCU	Vehicles/hour	PCU/hour
1	2	3	4	5	6	7	8=2+4+6	9=3+5+7
07.00-08.00	936	936	4	5.2	1888	377.6	2828	1318.8
12.00-13.00	504	504	4	5.2	1532	306.4	2040	815.6
16.30-17.30	104	104	0	0	216	43.2	320	147.2

The peak traffic volume during the two days of observation was recorded on Monday evening, October 12, 2024, between 16:30 and 17:30 CIT. Based on Table 3, the peak hour traffic volume for St. Usman Salengke (South) occurred in the morning between 07:00 and 08:00 CIT, with the number of light vehicles reaching 936 vehicles/hour, heavy vehicles at 4 vehicles/hour, and motorcycles at 1,888 vehicles/hour. All vehicle types were converted into passenger car units (PCU), resulting in 936 PCU/hour for light vehicles, 5.2 PCU/hour for heavy vehicles, and 377.6 PCU/hour for motorcycles. Thus, the peak hour volume was calculated to be 1318.8 PCU/hour.

Table 4. Traffic Volume on Usman Salengke Road (Northbound)

time	(LV) PCE = 1.0		(HV) PCE = 1.3		(MC) PCE = 0.2		Total	
	Vehicles	PCU	Vehicles	PCU	Vehicles	PCU	Vehicles/hour	PCU/hour
1	2	3	4	5	6	7	8=2+4+6	9=3+5+7
07.00-08.00	56	56	0	0	172	34,4	228	90.4
12.00-13.00	660	660	8	10.2	1108	221.6	1776	891.8
16.30-17.30	980	980	8	10.2	1964	392.8	2952	1383

Based on Table 4, the peak hour traffic volume for St. Usman Salengke (Northbound) occurred in the afternoon between 16:30 and 17:30 CIT, with the number of light vehicles reaching 980 vehicles/hour, heavy vehicles at 8 vehicles/hour, and motorcycles at 1,964 vehicles/hour. All vehicle types were converted into passenger car units (PCU), resulting in 980 PCU/hour for light vehicles, 10.2 PCU/hour for heavy vehicles, and 392.8 PCU/hour for motorcycles. Thus, the peak hour volume was calculated to be 1383 PCU/hour.

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Table 5. Traffic volume on the Malino main road section

time	(LV) PCE = 1.0		(HV) PCE = 1.3		(MC) PCE = 0.2		Total	
	Vehicles	PCU	Vehicles	PCU	Vehicles	PCU	Vehicles/hour	PCU/hour
1	2	3	4	5	6	7	8=2+4+6	9=3+5+7
07.00-08.00	628	628	4	5.2	964	192.8	1596	826
12.00-13.00	180	180	4	5.2	456	91.2	640	276.4
16.30-17.30	84	84	4	5.2	180	36	268	125.2

Based on Table 5, the traffic volume of St. Poros Malino, the peak hour volume occurs in the morning at 07.00-08.00 CIT, with the number of light vehicles of 628 vehicles/hour, heavy vehicles of 4 vehicles/hour and motorcycles of 964 vehicles/hour, all types of vehicles are converted to passenger car units (pcu), so that 628 pcu/hour are obtained for light vehicles, 5.2 pcu/hour for heavy vehicles and 192.8 for motorcycles, so that the peak hour volume is 826 pcu/hour.

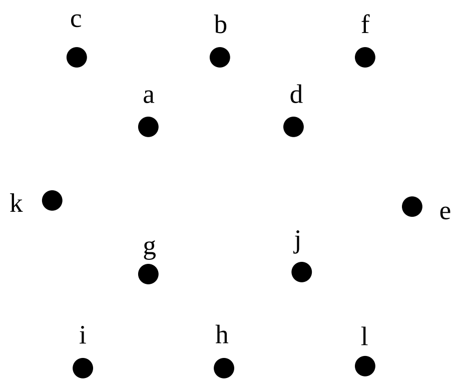
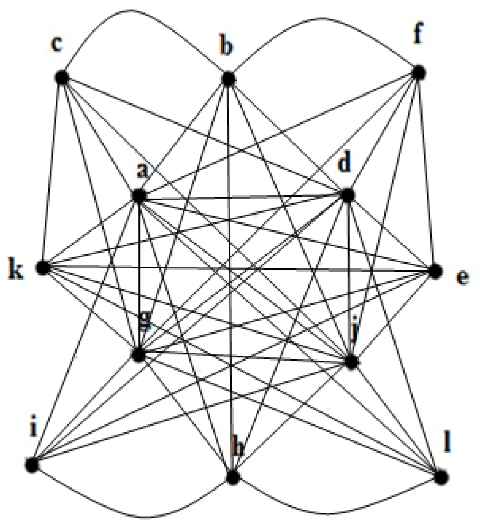
Table 6. Traffic volume on the K.H. Wahid Hasyim road section

time	(LV) PCE = 1.0		(HV) PCE = 1.3		(MC) PCE = 0.2		Total	
	Vehicles	PCU	Vehicles	PCU	Vehicles	PCU	Vehicles/hour	PCU/hour
1	2	3	4	5	6	7	8=2+4+6	9=3+5+7
07.00-08.00	102	102	0	0	141	28,2	243	130,2
12.00-13.00	60	60	0	0	92	18,4	152	78,4
16.30-17.30	196	196	4	5,2	444	88,8	644	290

Keterangan: (LV) = Light Vehicle; (HV) = Heavy Vehicle; (MC) = Motorcycle

Based on Table 6, the traffic volume of St. K.H. Wahid Hasyim, the peak hour volume occurs in the afternoon at 16.30-17.30 CIT, with the number of light vehicles of 196 vehicles/hour, heavy vehicles of 4 vehicles/hour and motorcycles of 444 vehicles/hour, all types of vehicles are converted to passenger car units (PCU), so that 196 pcu/hour is obtained for light vehicles, 5.2 PCU/hour for heavy vehicles and 88.8 for motorcycles, so that the peak hour volume is 290 pcu/hour. Changing the shape of the intersection into a compatible graph. Can be seen in the following table 7:

Table 7. Compatible graph forms

The Knots	Compatible graphs
	

In the Compatible Graph image in table 7, the Usman Salengke-Poros Malino-K.H.Wahid Hasyim intersection consists of 12 lanes with the names a, b, c, d, e, f, g, h, I, j, k, and l. Point a shows the traffic flow at a, point b shows the traffic flow at b, point c shows the traffic flow at c, and so do points d, e, f, g, h, I, j, k, and l. For more details, see Table 8, Compatible and Incompatible Flows.

Table 8. Compatible and incompatible currents

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

The intersection is changed into a compatible graph and compatible currents are obtained. Based on Table 4.6, it is obtained that nodes a, d, g, and j are compatible to all other nodes, after getting compatible currents, changing the compatible graph to a weighted directed dual graph and obtained for K.H. Wahid Hasyim street has a weight of 10, Usman Salengke street (south) has a weight of 12, Poros Malino street has a weight of 14, and Usman Salengke Utara street which has a weight of 12. Because Usman Salengke street (north) and Usman Salengke (south) have the same weight, so the number of phases at the intersection is three. Because nodes a, d, g, and l are compatible to all lanes, then from the Figure in table 7 Compatible graph, nodes a, d, g, and l are removed so that the Figure changes to the following Figure 5:

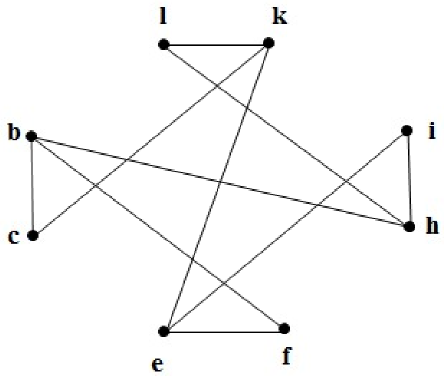


Figure 5. Compatible Graph

Next, transform the compatible graph into a weighted directed dual graph..

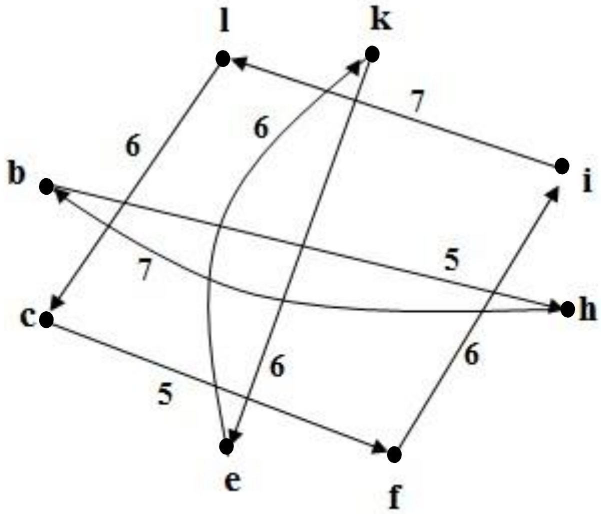


Figure 6. Weighted Directed Dual Graph

In Figure 6, nodes b and c are the traffic flows on K.H. Wahid Hasyim Street which have a weight of 10. Nodes e and f are the traffic flows on Usman Salengke Street (south) which have a weight of 12. Nodes i and h are the traffic flows on Poros Malino Street which have a weight of 14. Nodes k and l are the traffic flows on Usman Salengke Utara Street which have a weight of 12. Because Usman Salengke Street (north) and Usman Salengke (south) have the same weight, the number of phases at the intersection is three. After getting the number of phases, the next step is to determine the optimum cycle time (C_0)

$$C_0 = \frac{1.5 \times Lt + 5}{1 - FR} \quad ...(4)$$

To get the optimum cycle time, first determine:
Yellow time (R) = 5 seconds
Saturation flow at each intersection
For the north direction = 14 × 525 = 7350 pcu/hour

For the south direction = 7 × 525 = 3675 pcu/hour
For the east direction = 6 × 526 = 3150 pcu/hour
For the west direction = 1875 pcu/hour
Determine the value of y
y_u= 1383 / 7350 = 0.1881
y_s= 1318 / 3675 = 0.3586
y_t = 826 / 3150 = 0.2622
y_b = 290 / 1875 = 0.1546
$FR = \sum y_{max}$
= 0.3586 + 0.2622 +0.1546
= 0.7736

Determining lost time (Lt)
Lt = 2n + R
= 2 (3) + 5
= 11

So the optimum cycle time is:
$C_0 = \frac{1.5 \times Lt + 5}{1 - FR}$
$C_0 = \frac{1.5 \times Lt + 5}{1 - 0.7736}$
$C_0 = \frac{21.5}{0.2264}$
$C_0 = 95\ detik$

Then the maximum number of green time cycles is = $C_0 - Lt$
= 95 -11
= 84 detik

Green time
Fase I = $\frac{0.3586 \times 84}{0.7736}$
= $\frac{30.1224}{0.7736}$
= 39 second

Fase II = $\frac{0.2622 \times 84}{0.7736}$
= $\frac{22.0248}{0.7736}$
= 28 second

Fase III = $\frac{0.1546 \times 84}{0.7736}$
= $\frac{12.9864}{0.7736}$
= 17 second

Red time
Fase I = $C_0 - green\ time - yellow\ time$
= $95 - 39 - 5$
= 51 second

Fase II = $C_0 - green\ time - yellow\ time$
= $95 - 28 - 5$
= 62 second

Fase III = $C_0 - green\ time - yellow\ time$
= $95 - 17 - 5$
= 73 second

Table 9. New traffic light duration

Direction	green	yellow	Red
North	39	5	51
East	28	5	62
South	39	5	51
West	17	5	73

Based on the results that have been described previously, then a discussion was conducted on the application of graph theory in traffic light settings at the intersection of Street Usman Salengke, Poros Malino and K.H. Wahid Hasyim, Gowa Regency. The discussion includes intersection geometry data, vehicle volume, compatible graph, optimum cycle time, green time and red time. The geometric condition of the intersection of Usman Salengke Street(north), St. Poros Malino, St. Usman Salengke (south) and St. K.H. Wahid Hasyim does not have a median road, where the incoming and outgoing flows are on the same lane. At the intersection there is no canalization due to limited land.

This study utilizes a compatible graph theory approach to optimize traffic light arrangements at the four-way intersection of Street Usman Salengke-Poros Malino-K.H. Wahid Hasyim. By defining nodes and edges to represent compatible traffic flows, this approach successfully visualizes interactions between flows and identifies the most efficient phase for each lane. This approach differs from algorithms such as ELMOPP which are more complex and based on machine learning, because the focus of this study is on practical implementation based on road geometry and existing vehicle volume.

The optimum cycle time duration was calculated using the Webster method with results showing a cycle time of 95 seconds. Compared to the existing cycle in the field of 128 seconds, this result shows a significant reduction in waiting time. The green time for each phase was also revised, for example, on Usman Salengke Street(north) to 39 seconds from 26 seconds in the field. The same applies to other sections, such as on Poros Malino and K.H. Wahid Hasyim, where the proposed green time is more in line with the distribution of vehicle volume during peak hours.

This graph-based approach offers the advantage of identifying compatible flows that can move together without conflict [59], [60]. By eliminating fully compatible nodes such as nodes a, d, g, and l from the graph, this study successfully simplified the model into a weighted directed dual graph. This step reduces the complexity of the analysis, allowing for more accurate calculations of green and red times for each phase without the need for additional devices such as cameras or GPS as required in machine learning-based approaches.

The increase in efficiency is seen from the decrease in red time for all phases, such as on Street K.H. Wahid Hasyim which was reduced from 90 seconds to 73 seconds. This decrease contributes to a more balanced time distribution between moving and stopping flows, thereby reducing the risk of vehicle congestion on each lane. Overall, this approach provides a simple and applicable solution for traffic management at the study site, with results showing an increase in throughput and efficiency of the overall traffic system.

To ensure the validity of the results, additional simulations were conducted based on field data and the compatible graph model that has been created. This simulation uses MATLAB software to model changes in traffic light cycle times at the four-way intersection of Street Usman Salengke-Poros Malino-K.H. Wahid Hasyim. The simulation was conducted in two main scenarios: (1) application of the current model with a cycle time of 128 seconds (field) and (2) application of the research cycle time of 95 seconds with a green, yellow, and red distribution according to the Webster method. The following is the simulation output in the form of a comparison of the average waiting time between the current traffic light model (128 seconds) and the optimized model (95 seconds). This figure shows the difference in vehicle waiting time during peak hours.

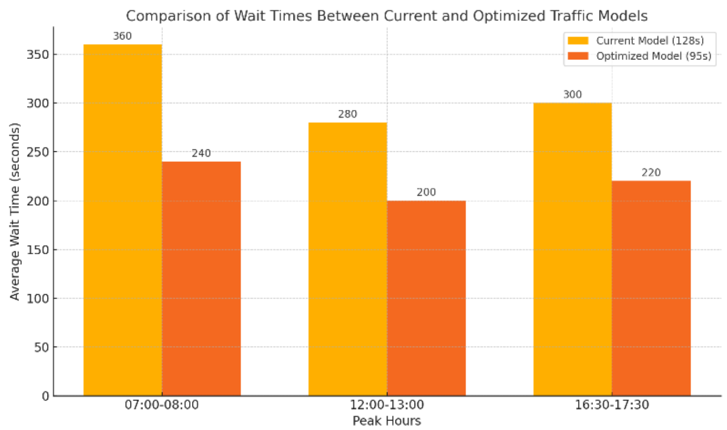


Figure 7. Results of comparative analysis of vehicle waiting times

In the first scenario, the total vehicle waiting time at all intersections reached an average of 360 seconds per vehicle during the morning peak hour (07.00–08.00 CIT). Meanwhile, in the second scenario, the waiting time decreased to 240 seconds per vehicle, indicating a reduction of 33.3%. This is in line with the findings of Sheriff [61], where reducing the duration of excessive traffic light cycles was shown to increase system throughput. With an optimal cycle time of 95 seconds, vehicle throughput increased by an average of 20% compared to the field setting.

Simulations show that a more proportional distribution of green time, such as increasing the green time for Usman Salengke Street(south) from 17 seconds to 39 seconds, provides more space for high-volume vehicle flows. The compatible graph model shows that eliminating nodes with full compatibility (nodes a, d, g, and l) is effective in minimizing conflicts. The simulation results prove that the frequency of long queues is reduced by 25%, which shows the effectiveness of the graph model in mapping and eliminating unnecessary flow conflicts. In comparison with adaptive systems such as the Sydney Coordinated Adaptive Traffic System (SCATS), the simulations show that the compatible graph-based approach has the advantage of significantly lower implementation costs. SCATS requires additional road sensors, while this approach only requires vehicle volume data that can be obtained manually, as suggested in the Sheriff study [58] on the cost-effective use of data in traffic management.

The simulation results show that the implementation of a 95-second cycle time not only reduces waiting time but also improves the efficiency of green time distribution. This is relevant to the ELMOPP (Edge Load Management and Optimization through Pseudo-flow Prediction) study by Sheriff [58], which suggests that graph-based models can provide local optimization solutions that approach the global optimum with low complexity. However, this research approach is simpler because it does not utilize technologies such as cameras or LSTM-based predictive algorithms. In addition, this finding supports the results of studies using the Split Cycle Offset Optimization Technique (SCOOT), where dynamic traffic light timing based on local data can reduce congestion by up to 30% in a case study of urban roads. This compatible graph-based approach provides similar results to much more complex methods such as SCATS and SCOOT, but at a lower cost and without requiring significant physical modifications to the road.

This study presents an innovative approach by utilizing compatible graph theory to optimize traffic light arrangements at four-way intersections on Street Usman Salengke, Poros Malino, and K.H. Wahid Hasyim. The novelty lies in the application of compatible graphs to efficiently model interactions between traffic flows, identify optimal phases, and simplify the complexity of cycle time calculations using methods based on road geometry and vehicle volume. The results show a decrease in traffic light cycle time from 128 seconds to 95 seconds, which has an impact on reducing vehicle waiting time and increasing traffic flow efficiency, while providing a practical solution without requiring additional technology such as machine learning-based sensors.

In the short term, this study provides direct benefits in the form of increasing the efficiency of traffic arrangements at the research location by reducing congestion during peak hours, especially through adjusting the duration of green and red that is more proportional to vehicle volume. This can increase traffic throughput and reduce travel time for road users [9], [62], [63]. In the long term, this simple and applicable compatible graph-based approach can be adopted by transport authorities in other regions with similar intersection characteristics. In addition, this method opens up opportunities for further development into an adaptive system that is able to adjust the duration of traffic lights based on changes in vehicle volume in real-time, creating a more responsive and sustainable traffic system. However, this approach has limitations in scalability, especially when applied to more complex road networks with interconnected intersections. Further research can consider combining the graph-based approach with simple machine learning algorithms, such as ITLC, to account for more complex traffic dynamics without significantly increasing operational costs..

5. CONCLUSION

This study successfully optimized the traffic light arrangement at the Usman Salengke-Poros Malino-K.H. Wahid Hasyim four-way intersection using the compatible graph theory approach and the Webster method. The results showed that the optimal cycle time duration was 95 seconds, which was more efficient compared to the current field setting of 128 seconds. With a more proportional distribution of green, yellow, and red times, this study successfully reduced vehicle waiting time by 33.3% and increased average vehicle throughput by 20%. The compatible graph-based approach was also effective in mapping compatible traffic flows, reducing conflicts, and simplifying the analysis model with a weighted directed dual graph. Simulations showed that this method offers high cost efficiency compared to adaptive systems such as SCATS, without requiring additional devices such as cameras or road sensors. Although the results are promising, this study has limitations in scalability, especially on more complex road networks. Therefore, further research is recommended to integrate the compatible graph approach with simple machine learning-based algorithms to account for more complex traffic dynamics and improve efficiency on interconnected urban road networks.

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REFERENCES

[1] Y. Deng, H. Chen, H. Liu, and Y. Li, "A Voxel Graph CNN for Object Classification with Event Cameras," *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit.*, vol. 2022-June, pp. 1162–1171, 2022, doi: 10.1109/CVPR52688.2022.00124.

[2] H. Liu, N. Yan, M. Mortazavi, and B. Bhanu, "Fully Convolutional Scene Graph Generation," *Proc. IEEE Comput. Soc. Conf. Comput. Vis. Pattern Recognit.*, pp. 11541–11551, 2021, doi: 10.1109/CVPR46437.2021.01138.

[3] J. Forsell, K. Forslund Frykedal, and E. Hammar Chiriac, "Group work assessment: assessing social skills at group level," *Small Gr. Res.*, vol. 51, no. 1, pp. 87–124, 2020, doi: 10.1177/1046496419878269.

[4] Y. Ren, H. Jiang, L. Zhang, R. Liu, and H. Yu, "HD-RMPC: A Hierarchical Distributed and Robust Model Predictive Control Framework for Urban Traffic Signal Timing," *J. Adv. Transp.*, vol. 2022, 2022, doi: 10.1155/2022/8131897.

[5] Y. Xing, W. Li, W. Liu, Y. Li, and Z. Zhang, "A Dynamic Regional Partitioning Method for Active Traffic Control," *Sustain.*, vol. 14, no. 16, pp. 1–16, 2022, doi: 10.3390/su14169802.

[6] C. Mylonas, E. Mitsakis, and K. Kepaptsoglou, "Criticality analysis in road networks with graph-theoretic measures, traffic assignment, and simulation," *Phys. A Stat. Mech. its Appl.*, vol. 629, p. 129197, 2023, doi: https://doi.org/10.1016/j.physa.2023.129197.

[7] K. Dresner and P. Stone, "A multiagent approach to autonomous intersection management," *J. Artif. Intell. Res.*, vol. 31, pp. 591–656, 2008, doi: 10.1613/jair.2502.

[8] D. GruGruyer, O. Orfila, S. Glaser, A. Hedhli, N. Hautière, and A. Rakotonirainy, "Are Connected and Automated Vehicles the Silver Bullet for Future Transportation Challenges? Benefits and Weaknesses on Safety, Consumption, and Traffic Congestion," *Front. Sustain. Cities*, vol. 2, no. January, pp. 1–24, 2021, doi: 10.3389/frsc.2020.607054.

[9] M. Eom and B. I. Kim, "The traffic signal control problem for intersections: a review," *Eur. Transp. Res. Rev.*, vol. 12, no. 1, 2020, doi: 10.1186/s12544-020-00440-8.

[10] Y. Alsaawy, A. Alkhodre, A. A. Sen, A. Alshanqiti, W. A. Bhat, and N. M. Bahbouh, "A Comprehensive and Effective Framework for Traffic Congestion Problem Based on the Integration of IoT and Data Analytics," *Appl. Sci.*, vol. 12, no. 4, 2022, doi: 10.3390/app12042043.

[11] H. Hsiao, J. Chang, and P. Simeonov, "Preventing Emergency Vehicle Crashes: Status and Challenges of Human Factors Issues," *Hum. Factors*, vol. 60, no. 7, pp. 1048–1072, 2018, doi: 10.1177/0018720818786132.

[12] I. O. Olayode, L. K. Tartibu, M. O. Okwu, and U. F. Uchechi, "Intelligent transportation systems, un-signalized road intersections and traffic congestion in Johannesburg: A systematic review," *Procedia CIRP*, vol. 91, no. March, pp. 844–850, 2020, doi: 10.1016/j.procir.2020.04.137.

[13] G. Muhiuddin, M. Mohseni Takallo, Y. B. Jun, and R. A. Borzooei, "Cubic graphs and their application to a traffic flow problem," *Int. J. Comput. Intell. Syst.*, vol. 13, no. 1, pp. 1265–1280, 2020, doi: 10.2991/IJCIS.D.200730.002.

[14] J. Guo and I. Harmati, "Lane-changing decision modelling in congested traffic with a game theory-based decomposition algorithm," *Eng. Appl. Artif. Intell.*, vol. 107, no. October 2021, p. 104530, 2022, doi: 10.1016/j.engappai.2021.104530.

[15] D. SUI, W. XU, and K. ZHANG, "Study on the resolution of multi-aircraft flight conflicts based on an IDQN," *Chinese J. Aeronaut.*, vol. 35, no. 2, pp. 195–213, 2022, doi: 10.1016/j.cja.2021.03.015.

[16] A. M. de Souza, C. A. R. L. Brennand, R. S. Yokoyama, E. A. Donato, E. R. M. Madeira, and L. A. Villas, "Traffic management systems: A classification, review, challenges, and future perspectives," *Int. J. Distrib. Sens. Networks*, vol. 13, no. 4, 2017, doi: 10.1177/1550147716683612.

[17] K. Nellore and G. P. Hancke, "A survey on urban traffic management system using wireless sensor networks," *Sensors (Switzerland)*, vol. 16, no. 2, 2016, doi: 10.3390/s16020157.

[18] N. Ali, B. Afwadzi, I. Abdullah, and M. I. Mukmin, "Interreligious Literacy Learning as a Counter-Radicalization Method: A New Trend among Institutions of Islamic Higher Education in Indonesia," *Islam Christ. Relations*, vol. 32, no. 4, pp. 383–405, 2021, doi: 10.1080/09596410.2021.1996978.

[19] S. Damadam, M. Zourbakhsh, R. Javidan, and A. Faroughi, "An Intelligent IoT Based Traffic Light Management System: Deep Reinforcement Learning," *Smart Cities*, vol. 5, no. 4, pp. 1293–1311, 2022, doi: 10.3390/smartcities5040066.

[20] H. Singh and S. J. Miah, "Smart education literature: A theoretical analysis," *Educ. Inf. Technol.*, vol. 25, no. 4, pp. 3299–3328, 2020, doi: 10.1007/s10639-020-10116-4.

[21] I. O. Olayode, L. K. Tartibu, M. O. Okwu, and A. Severino, "Comparative traffic flow prediction of a heuristic ANN model and a hybrid ANN-PSO model in the traffic flow modelling of vehicles at a four-way signalized road intersection," *Sustain.*, vol. 13, no. 19, 2021, doi: 10.3390/su131910704.

[22] Z. Nie and H. Farzaneh, "Real-time dynamic predictive cruise control for enhancing eco-driving of electric vehicles, considering traffic constraints and signal phase and timing (SPaT) information, using artificial-neural-network-based energy consumption model," *Energy*, vol. 241, 2022, doi: 10.1016/j.energy.2021.122888.

[23] B. Ibrokhimov, Y. J. Kim, and S. Kang, "Biased Pressure: Cyclic Reinforcement Learning Model for Intelligent Traffic Signal Control," *Sensors*, vol. 22, no. 7, 2022, doi: 10.3390/s22072818.

[24] R. Besenczi, N. Bátfai, P. Jeszenszky, R. Major, F. Monori, and M. Ispány, *Large-scale simulation of traffic flow using Markov model*, vol. 16, no. 2 February. 2021. doi: 10.1371/journal.pone.0246062.

[25] R. Ekhlakov and N. Andriyanov, "Multicriteria Assessment Method for Network Structure Congestion Based on Traffic Data Using Advanced Computer Vision," *Mathematics*, vol. 12, no. 4, 2024, doi: 10.3390/math12040555.

[26] S. M. Abdullah *et al.*, "Optimizing Traffic Flow in Smart Cities: Soft GRU-Based Recurrent Neural Networks for

Enhanced Congestion Prediction Using Deep Learning," *Sustain.*, vol. 15, no. 7, 2023, doi: 10.3390/su15075949.
[27] F. Zanlungo, C. Feliciani, Z. Yücel, X. Jia, K. Nishinari, and T. Kanda, "A pure number to assess 'congestion' in pedestrian crowds," *Transp. Res. Part C Emerg. Technol.*, vol. 148, no. July 2022, p. 104041, 2023, doi: 10.1016/j.trc.2023.104041.
[28] X. Xin, K. Liu, H. Li, and Z. Yang, "Maritime traffic partitioning: An adaptive semi-supervised spectral regularization approach for leveraging multi-graph evolutionary traffic interactions," *Transp. Res. Part C Emerg. Technol.*, vol. 164, no. May, p. 104670, 2024, doi: 10.1016/j.trc.2024.104670.
[29] S. C. Dimri *et al.*, "Modeling of traffic at a road crossing and optimization of waiting time of the vehicles," *Alexandria Eng. J.*, vol. 98, no. May, pp. 114–129, 2024, doi: 10.1016/j.aej.2024.04.050.
[30] Y. Li, Z. Qin, and C. M. Zhu, "Optimal design of transportation signal control at the intersection based on Webster signal timing method," *J. Phys. Conf. Ser.*, vol. 1972, no. 1, 2021, doi: 10.1088/1742-6596/1972/1/012130.
[31] O. R. Sikas, G. S. Mada, F. M. A Blegur, A. G. Nabu, and A. History, "http://ejournal.radenintan.ac.id/index.php/desimal/index Application of graph theory and webster method in traffic light settings at the tulip intersection in kefamenanu city ARTICLE INFO ABSTRACT," *Desimal J. Mat.*, vol. 6, no. 3, pp. 323–336, 2023, doi: 10.24042/djm.
[32] J. Sandefur, E. Lockwood, E. Hart, and G. Greefrath, "Teaching and learning discrete mathematics," *ZDM - Math. Educ.*, vol. 54, no. 4, pp. 753–775, 2022, doi: 10.1007/s11858-022-01399-7.
[33] K. K. Aase, "Optimal Spending Strategies for Sovereign Wealth Funds Using a Discrete-Time Life Cycle Model †," *J. Risk Financ. Manag.*, vol. 17, no. 8, 2024, doi: 10.3390/jrfm17080327.
[34] V. Morozov and S. Iarkov, "Formation of the traffic flow rate under the influence of traffic flow concentration in time at controlled intersections in Tyumen, Russian federation," *Sustain.*, vol. 13, no. 15, 2021, doi: 10.3390/su13158324.
[35] S. Rojas-Blanco, A. Cerezo- Narváez, M. Otero-Mateo, and S. Sáez-Martínez, "Adjacency List Algorithm for Traffic Light Control Systems in," *Systems*, vol. 12, pp. 1–24, 2024, doi: 10.3390/systems12120539.
[36] W. Zhang, "Countermeasures for Urban Traffic Congestion in China from the Perspective of System Dynamics," *Comput. Intell. Neurosci.*, vol. 2022, 2022, doi: 10.1155/2022/3509902.
[37] D. L. Sokido, "Measuring the level of urban traffic congestion for sustainable transportation in Addis Ababa, Ethiopia, the cases of selected intersections," *Front. Sustain. Cities*, vol. 6, 2024, doi: 10.3389/frsc.2024.1366932.
[38] Y. Berhanu, D. Schröder, B. T. Wodajo, and E. Alemayehu, "Machine learning for predictions of road traffic accidents and spatial network analysis for safe routing on accident and congestion-prone road networks," *Results Eng.*, vol. 23, no. July, 2024, doi: 10.1016/j.rineng.2024.102737.
[39] Q. Zhu, Y. Liu, M. Liu, S. Zhang, G. Chen, and H. Meng, "Intelligent planning and research on urban traffic congestion," *Futur. Internet*, vol. 13, no. 11, pp. 1–17, 2021, doi: 10.3390/fi13110284.
[40] C. Chairani, I. Jaya, and H. Cipta, "Optimasi Waktu Tunggu Total Dengan Metode Webster dalam Mengatasi Kemacetan Lalu Lintas Persimpangan Street Kolonel Yos Sudarso," *FARABI J. Mat. dan Pendidik. Mat.*, vol. 4, no. 2, pp. 175–180, 2021, doi: 10.47662/farabi.v4i2.226.
[41] H. Budianto, A. Amrullah, W. Wahidaturrahmi, and A. Arjudin, "Optimalisasi Waktu Tunggu Lampu Lalu Lintas menggunakan Simulasi Monte Carlo di Simpang Lima Ampenan Kota Mataram," *Griya J. Math. Educ. Appl.*, vol. 2, no. 3, pp. 691–699, 2022, doi: 10.29303/griya.v2i3.208.
[42] M. Mu and M. Yuan, "Research on a personalized learning path recommendation system based on cognitive graph with a cognitive graph," *Interact. Learn. Environ.*, vol. 32, no. 8, pp. 4237–4255, 2024.
[43] P. Tang, Z. Yao, J. Luan, and J. Xiao, "How information presentation formats influence usage behaviour of course management systems: flow diagram navigation versus menu navigation," *Behav. Inf. Technol.*, vol. 41, no. 2, pp. 383–400, 2022.
[44] S. M. Cheema, S. Tariq, and I. M. Pires, "A natural language interface for automatic generation of data flow diagram using web extraction techniques," *J. King Saud Univ. - Comput. Inf. Sci.*, vol. 35, no. 2, pp. 626–640, 2023, doi: 10.1016/j.jksuci.2023.01.006.
[45] R. Wahyudi *et al.*, "Penerapan algoritma dijkstra untuk optimasi ke empat gerbang kampus menggunakan python," *JATI (Jurnal Mhs. Tek. Inform.*, vol. 8, no. 6, pp. 12073–12078, 2024.
[46] S. Alshayeb, A. Stevanovic, N. Mitrovic, and E. Espino, "Traffic Signal Optimization to Improve Sustainability: A Literature Review," *Energies*, vol. 15, no. 22, 2022, doi: 10.3390/en15228452.
[47] J. Gu, M. Lee, C. Jun, Y. Han, Y. Kim, and J. Kim, "Traffic signal optimization for multiple intersections based on reinforcement learning," *Appl. Sci.*, vol. 11, no. 22, 2021, doi: 10.3390/app112210688.
[48] I. Kabashkin, "Model of Multi Criteria Decision-Making for Selection of Transportation Alternatives on the Base of Transport Needs Hierarchy Framework and Application of Petri Net," *Sustain.*, vol. 15, no. 16, 2023, doi: 10.3390/su151612444.
[49] K. Abdou, O. Mohammed, G. Eskandar, A. Ibrahim, P. A. Matt, and M. F. Huber, "Smart nesting: estimating geometrical compatibility in the nesting problem using graph neural networks," *J. Intell. Manuf.*, vol. 35, no. 6, pp. 2811–2827, 2024, doi: 10.1007/s10845-023-02179-0.
[50] O. Mansourihanis, M. J. Maghsoodi Tilaki, S. Yousefian, and A. Zaroujtaghi, "A Computational Geospatial Approach to Assessing Land-Use Compatibility in Urban Planning," *Land*, vol. 12, no. 11, pp. 1–19, 2023, doi: 10.3390/land12112083.
[51] A. Stupin, L. Kazakovtsev, and A. Stupina, "Control of traffic congestion by improving the rings and optimizing the phase lengths of traffic lights with the help of anylogic," *Transp. Res. Procedia*, vol. 63, pp. 1104–1113, 2022, doi: 10.1016/j.trpro.2022.06.113.
[52] D. R. Aleko and S. Djahel, "An efficient adaptive traffic light control system for urban road traffic congestion reduction in smart cities," *Inf.*, vol. 11, no. 2, pp. 1–20, 2020, doi: 10.3390/info11020119.
[53] A. Preston and S. S. Pulugurtha, "Simulating and assessing the effect of a protected intersection design for bicyclists on

traffic operational performance and safety," *Transp. Res. Interdiscip. Perspect.*, vol. 9, no. February, p. 100329, 2021, doi: 10.1016/j.trip.2021.100329.

[54] A. Shams and M. Zlatkovic, "Effects of capacity and transit improvements on traffic and transit operations," *Transp. Plan. Technol.*, vol. 43, no. 6, pp. 602–619, 2020.

[55] K. James Singh *et al.*, "Recent Advances in Micro-LEDs Having Yellow–Green to Red Emission Wavelengths for Visible Light Communications," *Micromachines*, vol. 14, no. 2, p. 478, 2023, doi: 10.3390/mi14020478.

[56] Q. Wang, Q. Zhang, X. Liang, Y. Wang, C. Zhou, and V. I. Mikulovich, "Traffic lights detection and recognition method based on the improved yolov4 algorithm," *Sensors*, vol. 22, no. 1, pp. 1–20, 2022, doi: 10.3390/s22010200.

[57] P. Savary, J. C. Foltête, H. Moal, G. Vuidel, and S. Garnier, "graph4lg: A package for constructing and analysing graphs for landscape genetics in R," *Methods Ecol. Evol.*, vol. 12, no. 3, pp. 539–547, 2021, doi: 10.1111/2041-210X.13530.

[58] X. Xiao *et al.*, "A dual-path dynamic directed graph convolutional network for air quality prediction," *Sci. Total Environ.*, vol. 827, p. 154298, 2022.

[59] Z. Şuvak, İ. K. Altınel, and N. Aras, "Minimum cost flow problem with conflicts," *Networks*, vol. 78, no. 4, pp. 421–442, 2021.

[60] G. Pauer and Á. Török, "Improving Highly Automated Traffic Management Models Using Alternative Graph Structures Simultaneously," *Appl. Sci.*, vol. 14, no. 22, 2024, doi: 10.3390/app142210484.

[61] F. Sheriff, "ELMOPP: an application of graph theory and machine learning to traffic light coordination," *Appl. Comput. Informatics*, vol. 20, no. 3–4, pp. 217–230, 2024, doi: 10.1108/ACI-07-2020-0035.

[62] A. Donkers, D. Yang, and M. Viktorović, "Influence of driving style, infrastructure, weather and traffic on electric vehicle performance," *Transp. Res. Part D Transp. Environ.*, vol. 88, no. October, 2020, doi: 10.1016/j.trd.2020.102569.

[63] G. Yannis, D. Nikolaou, A. Laiou, Y. A. Stürmer, I. Buttler, and D. Jankowska-Karpa, "Vulnerable road users: Cross-cultural perspectives on performance and attitudes," *IATSS Res.*, vol. 44, no. 3, pp. 220–229, 2020, doi: 10.1016/j.iatssr.2020.08.006.