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Traffic lights time strategy for T-junctions of toll road gate

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ABSTRACT

Vehicles wishing to pass on the toll road must diverge from the traffic flow on public roads. The toll road movement consists of low vehicles (LV) and heavy vehicles (HV). The public road movement is a mixed traffic flow consisting of LV, HV, motorcycles, and unmotorized vehicles. Traffic lights are used at the T-junction of the toll road gate for travel safety management. The traffic lights that implement a fixed-time strategy should be optimized for efficiency. This study aims to review the safety of travel management at T-junctions for the toll road gate when adaptive traffic lights are used. The structural complexity of mathematical modeling with Petri net is used to analyze and measure the feasibility study. Results illustrate that the structural complexity of the traffic lights that implement a fixed time strategy equals 0.387. It is equal to 0.489 for the adaptive traffic lights. The structural complexity of adaptive traffic lights is 25% higher than conventional systems that implement a fixed-time strategy. The adaptive traffic lights time strategy is feasible for travel safety for road users. The travel time is efficient and comfortable because the delay is low. Furthermore, traffic lights can adjust to the demand of vehicles queuing.

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1. INTRODUCTION

The T-junctions are prepared for the gate of the toll road. Therefore, they play a role in providing services for vehicles that will enter the toll road. In addition, vehicles that have ended their travel on the toll road and wish to join the traffic flow on public roads should also pass these T-junctions.

The regulations state that the vehicles passing on the toll road are limited. They are low vehicles (LV) and heavy vehicles (HV). The number of vehicles passing on the toll road is small compared to those that pass through on public roads. The vehicles must be road worthy and capable of being driven at high speeds. The existence of vehicles entering the toll road and vehicles leaving the toll road is incidental. They only sometimes exist at every traffic light cycle. The toll road is an intercity freeway [1].

The vehicles flow on public roads is always heavy traffic. Its characteristics are heterogeneous. The mixed movement on public roads consists of LV, HV, motorcycle (MC), and unmotorized vehicles (UM) [2]. It knows that vehicles with different types significantly vary in their static conditions, dynamic behavior, and operating system characteristics [3]. Therefore, when passing on it, the driver must be more patient due to the movement of all vehicles. In addition, they must interact with each other on public roads.

Vehicles wishing to pass on the toll road must diverge from the traffic of public roads. Likewise, vehicles have just ended through the toll road and want to rejoin the traffic flow on public roads. Therefore, vehicles entering and leaving the toll road must conflict with traffic flows on public roads. Traffic flow conflicts in different directions can cause congestion, inefficiency, and the potential for accidents [3].

So far, the traffic lights have successfully solved the flow of vehicle conflicts at the T-junction. Since the beginning, a fixed time strategy for traffic lights has been used to create time-sharing. It has been accomplished for safe travel. However, heavy traffic on public roads often must stop even though no vehicles wish to enter or exit the toll road gate. The fixed-time strategy makes it impossible to ignore the sequence of traffic light phases of vehicle travel from a particular direction even though no vehicles are queuing. The traffic lights on one arm of the T-junction remain green even though the queue of vehicles in that direction has ended. It generates a high travel delay [4]. The green-time signals of each lane must be based on the traffic density [5].

We have to solve this inefficient problem. The traffic light schedule must be efficient. Furthermore, this paper aims to review travel management when adaptive traffic lights are used. The sequence of traffic light phases must be designed to adjust to the demand of vehicle traffic. We must compare the results of the adaptive system with the previous state when it used a fixed-time strategy. The measurement is based on the control system's feasibility, especially on the increase in its structural complexity. For mathematical modeling of structural complexity, Petri net is used.

Structural complexity is not the same as computational complexity. Computational complexity measures the amount of computational resources (time and space) consumed by a particular algorithm when it is executed [6]. According to *Kamus Besar Bahasa Indonesia*, or Great Dictionary of the Indonesian Language [7], structural complexity is more likely an indicator of the interrelationships within a project, program, or portfolio that affect how these relationships will be managed and the skills required to manage them.

The main topic of this study is to review the traffic light structure complexity, especially at the T-junctions of the toll road gate that implements the adaptive system to control vehicle flow. The other researchers had never previously discussed this traffic light design, primarily implemented for unique junctions.

We also refer to the following previous research. Cahyono *et al.* [4] have written a paper entitled: Modification of the Norwegian traffic lights states reduce travel delay. They apply an adaptive control system for traffic lights set for travel efficiency. They implement an on-demand control system for traffic lights set that ensures safe travel. Cahyono *et al.* [8] reviewed the impact of setting traffic lights on traffic jams. Yulianto and Setiono [3] wrote a paper entitled: Traffic signal controller for mixed traffic conditions. The traffic signal controller is able to guarantee travel safety and delay. It used an adaptive traffic lights control system. Tristono *et al.* [9] modeled traffic flow at signalized intersections with railway crossings which can reduce delay.

Hartanti [10] said that one of the leading causes of traffic vehicle queues at intersections is because the traffic light settings are disproportionate to the volume of existing vehicle traffic. Mohamed and Radwan [11] wrote that until now, a sensor design has yet to be developed that can detect road traffic density and provide intelligent solutions in real terms. The intelligent system should be able to build dynamic time interval settings and have learning capabilities, emergency priority management, and intelligent functionality. In general, they still use conventional design approaches.

Abdul Kareem and Hoomod [12] proposed a traffic light signal system with three modules: the intelligent visual monitoring module, the intelligent traffic light control module, and the intelligent recommendation module for emergency vehicles. The monitor module is capable of identifying the traffic volume on the road. The intelligent traffic light control module is to build a coordination system of many intersections in a city to improve the flow of vehicles. Finally, the intelligent recommendation module offers a priority member for emergency vehicles. Sabri and El Kamoun [13] stated that conventional traffic light systems offer a distributed solution for managing congestion but usually fail to regulate traffic flow in reality. Desmira *et al.* [14] created an intelligent traffic light using fuzzy logic inference for an adaptive traffic light. It is to manage the dynamics of the vehicles at an intersection.

Huang and Chung [15] used a timed colored Petri net to model and analyze the traffic light control systems. The traffic light control prevents traffic congestion among vehicles [16]. Bolla *et al.* [17] studied one-way system traffic at the junction of Straat A of Kupang City. Based on Manual Kapasitas Jalan Indonesia (MKJI) or Indonesian Highway Capacity Manual, their research states that the system is feasible. Pesik *et al.* [18] conducted a traffic lights study for road crossers. They studied its effect on the number of vehicles queued up. It states that they must improve the pedestrian culture of disciplined behavior.

Machdani *et al.* [19] designed a traffic light control system for emergency services based on IoT. It is an innovation to regulate traffic lights for ambulances crossing the intersection. Pangemanana *et al.* [20] designed an intelligent traffic light control system using a microcontroller and camera. The study developed a method for estimating the queue length. Finally, Djavendra *et al.* [21] designed a traffic light control system for vehicle density identification. The research proposes an automatic traffic light control system to predict vehicle density using pixel image processing techniques.

Wibowo *et al.* [22] implemented Max-Plus Algebra to set the queue system on the traffic lights. Their research assumed the traffic light problem to be a discrete event system (DES). Barzegar *et al.* [23] built fuzzy logic inference for a traffic signal control using the colored Petri net that provides intelligent traffic light systems for multiple junctions. The traffic lights can estimate traffic volume. It can send parameters to the control center and receive them from it.

Yaqub and Li [24] modeled and analyzed connected traffic intersections using modified binary Petri nets. They used the concept of modified binary Petri nets to solve the conflict problem. An *et al.* [25] used colored Petri nets to model and analyze the control systems. They verified their model based on the Petri net properties: reachable states, boundedness, liveness, and fairness. The experiment results showed that their control model provides better transit vehicles at the intersections.

2. METHOD

The analysis of the traffic lights control system is based on mathematical modeling. First, construct a Petri net traffic lights model with a fixed-time strategy. Next, we build an adaptive traffic light model and compare the structural complexity.

2.1. Petri Net

Petri net elements are places (P) states space represented by circles; boxes are transitions (T) as the trigger device for transforming token from the initial to the next state, and arcs. The model has arcs for creating a sequence of states flow. Petri net is the mathematical description of state flow. The model manifested graphically. It makes it exciting, and so the user is easy to understand. The number of tokens in the place indicated the happening state. It is called "Marking."

An arc has weight. The minimum number of tokens in the upstream state implies readiness to fire in its downstream transition. The weight of arcs between an upstream place and a transition determines the number of tokens required to be enabled. The weight of arcs determines the number of tokens consumed/produced [19], [26].

The reachability is part of the network's performance, which is reachable from the initial state in a graph. All states must be reachable by firing several enabled transitions from the initial state. A transition is live if it is fireable for markings. A Petri net must be live. At least a live transition exists in the network. A place is safe if the token count does not exceed 1 in any of the markings. A Petri net is safe if each place is safe. This term is a generalization of safeness, while a place is bounded with bound k if the token count does not exceed k in any marking. A Petri net is k-bounded if each place is k-bounded. A conservative Petri net has the number of tokens constant in any markings [15]. Reachability states, liveness, k-bounded, and conservativeness are the properties of the Petri net. For simulation, Petri Net Simulator 2.0 is used.

2.2. The structural complexity

The cross-sectoral variable that was analyzed is the complexity of the traffic lights control system. So, the Petri net model diagram is required to compare the structure of the traffic lights control system using a fixed time strategy and the adaptive system. In addition, it includes testing the feasibility of adaptive traffic lights. Its structural complexity measurement formulas refer to Taiping and Peisi [27].

3. RESULTS AND DISCUSSION

The traffic flow on the public road moves in two directions, namely from east to west and vice versa. It is left-hand traffic in which the traffic movement is on the left side of the road. It refers to Figure 1. The toll road gate is located north of the T-junction. Vehicles passing through the T-junction from east to west do not need to stop because they already have separate lanes. Vehicles from the west that intend to go to the toll road gate and vehicles from the toll road gate moving towards the east arm do not stop. They may continue their travel to their destination directly. Their flow is unscheduled by traffic lights because it has no conflicts with other vehicle flows.

The traffic lights play a role in scheduling the flow of vehicles from the east towards the toll gate, vehicles from the west arm wishing to move straight towards, and vehicles coming out of the toll gate heading for the west arm.

The traffic lights setting applies to three phases when implementing a fixed time strategy: the phase east, the phase west, and the phase north. Figures 2 and 3 present the traffic lights Petri net model. The actual traffic light states have three colors, i.e., green, yellow, and red. In the model, the signals are represented using circles. The role of the white states is as the controllers. The state that is being turned on is marked with a black dot/ token in it.

The traffic lights should play a role in building vehicle movements to avoid traffic conflicts at the T-junction. Therefore, Petri nets must satisfy several properties to be a valid model. First, the traffic light model should have the correct order and it does not allow deadlock. The sequence should be able to serve all the traffic light phases and be returnable to the initial state. Finally, it analyzes this model using the coverability state, invariants, and Petri net simulation.

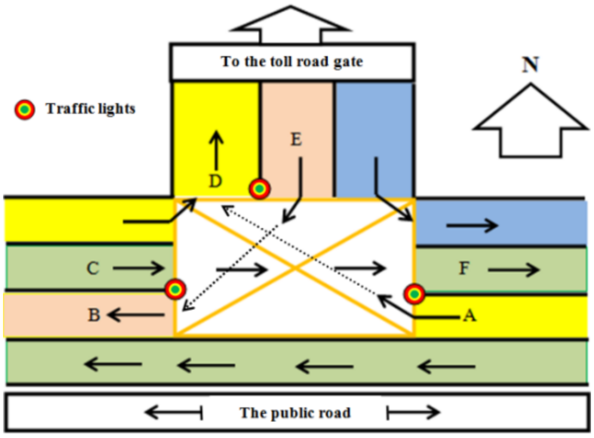

Figure 1. T-junction and its flow, which applies the left-hand traffic; at T-junction, the vehicle's movement to turn left is allowed without stopping due to traffic light signals; pedestrians are very rare at the junction and are assumed to be non-existent

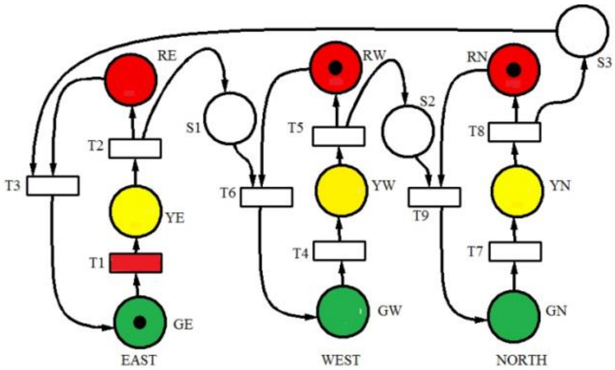

Figure 2. The petri net model of three phases traffic lights using fixed time strategy

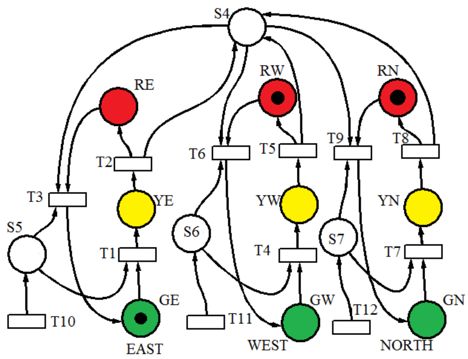

Figure 3. The petri net model of adaptive traffic lights using order demand

3.1. Place-invariant of the model

A place-invariant of the traffic lights model indicates that the number of tokens in reachable markings satisfies several linear invariants that don't change at all times. Invariant (1) up to Invariant (6) are applied to traffic lights with a fixed time strategy and adaptive system. Invariant (1) to Invariant (3) states that only one signal lights up at a traffic light phase. Invariant (1) represents the eastern traffic light phase. Only one signal is on when using a standard traffic light. The yellow and red signals go out when the green light is on. The green and red signals must go out when the yellow light is on. Also, the green and yellow signals go out when the red light is on. The signals cannot flash simultaneously. Invariant (2) presents the northern traffic light phase. Invariant (3) is written for the west traffic light phase.

$$M(GE) + M(YE) + M(RE) = 1 \quad (1)$$

$$M(GN) + M(YN) + M(RN) = 1 \quad (2)$$

$$M(GW) + M(YW) + M(RW) = 1 \quad (3)$$

Invariant (4) states that if the west and east traffic light phases turn green or yellow, the northern traffic light phase should light red. It is a guarantee of travel safety. The vehicle signals from the west and east may light green or yellow if the flow of vehicles from the north stops or the traffic light signal is red. It also indicates that the vehicle signals from the west and east cannot be simultaneously light green or yellow. The methods in Invariant (5) and Invariant (6) are used so that the west and east traffic light phase lights up red, respectively.

$$M(GW) + M(YW) + M(GE) + M(YE) = M(RN) \qquad While\ M(RN) = 1 \tag{4}$$

$$M(GN) + M(YN) + M(GE) + M(YE) = M(RW) \qquad While\ M(RW) = 1 \tag{5}$$

$$M(GW) + M(YW) + M(GN) + M(YN) = M(RE) \qquad While\ M(RE) = 1 \tag{6}$$

Invariant (7) applies to traffic lights using a fixed-time strategy. It establishes synchronous traffic lights on the west, east, and north arms. Invariant (8) applies to adaptive traffic lights without representing the control/ sensor system. It builds traffic light order demand due to vehicle queues on each arm of the T-junction.

$$M(GE) + M(YE) + M(GN) + M(YN) + M(GW) + M(YW) + M(S1) + M(S2) + M(S3) = 1 \tag{7}$$

$$M(GE) + M(YE) + M(GN) + M(YN) + M(GW) + M(YW) + M(S4) = 1 \tag{8}$$

The token in the Petri net model is either 0 or 1 only. The term 0 is off, and one is on. The coverability state presents the reachability tree. It contains all finite states that may occur. Coverability can explain several aspects, i.e., safeness, liveness, and boundedness. It uses row vectors consisting of elements. The coverability state also presents the sequence of the firing transitions. It starts at the initial state and must return to its initial state again.

3.2. Coverable states of traffic lights

The firing transitions sequence reflecting the coverable states for the fixed time strategy is T1⟶ T2 ⟶T6 ⟶ T4 ⟶T5 ⟶ T9 ⟶ T7 ⟶ T8 ⟶ T3. It returns to T1, and so on. Thus, it establishes a cycle of traffic lights that are repeated. It proves the traffic light model is correct and fulfills all its properties.

The sequence of firing transitions of phase east is T10 ⟶T3 ⟶ T10 ⟶T1 ⟶ T2. The order of firing transitions while phase west is T11 ⟶T6 ⟶ T11 ⟶T4 ⟶ T5. Finally, when the north phase is T12 ⟶T9 ⟶ T12 ⟶T7 ⟶ T8. It reflects the coverable states for adaptive traffic lights.

The adaptive traffic light phase sequence cannot repeat the same phase directly. It must serve the other phases first. The transitions T10, T11, and T12 fire twice in their phases. The first fire is the command to start to turn on the green signal, and the second is to end the green signal. It is based on vehicle sensors installed on all three arms.

The sequence of phases and the duration of the green signal are fixed when traffic lights use the Fixed Time Strategy. The sequence of phases is east to west, then north. It repeats itself to build a traffic light cycle. The states of traffic lights for the east, west, and north phases were simulated, respectively. The states of traffic lights of adaptive traffic lights while phase east, phase west, and phase north were simulated, respectively. The sequence of phases and the green signal duration depend on the traffic demand.

3.3. Structural complexity

Figure 4 is the Petri net model of adaptive traffic lights. The green signal for each phase lights up according to demand. If a vehicle queues in the associated phase, the green signal will turn on in the following sequence/order. A phase can be skipped if there are no vehicles queued up. The system uses vehicle detectors.

Visually, the traffic light structure that implements a fixed-time strategy differs from adaptive traffic lights. Figure 2 looks simple, and Figure 3 appears very complicated. The result of the structural complexity is presented in Table 1. The complexity of the structure is in the interval of 0 – 1. The systems are simple if they have a level of structural complexity close to 0. The score of the ideal system is approximately 0.5. A system with a score leading to 1 is said to have a high complexity structure. Complex systems usually require more investment, installation, and maintenance costs.

It is based on Table 1. When it uses a fixed-time strategy, the structural complexity (C_s) of traffic lights equals 0.387. Therefore, it is a simple system. On the other hand, the structural complexity of the adaptive traffic lights is equal to 0.489. Consequently, it represents an ideal system.

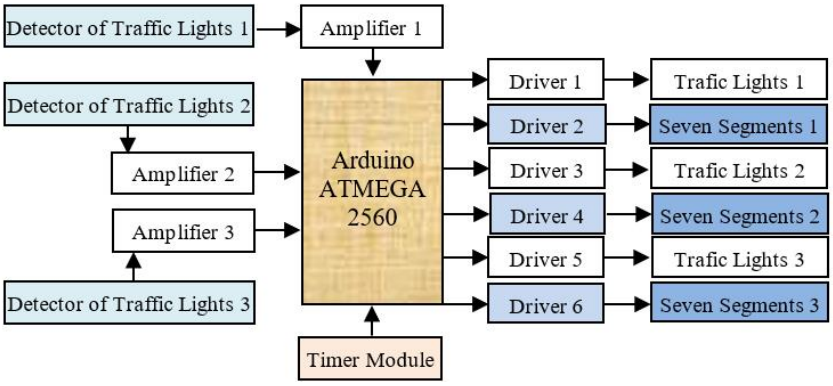

Figure 4. Block diagram for a traffic light control system with three phases

Table 1. The structural complexity score

Therm	The Traffic Lights Type	
	Fixed Time Strategy	Adaptive System
	Score/Number of Elements	
X	21	22
P	12	13
T	9	12
aλa	0.095	0.1145
Cn	0.9	0.92
Cp	1/6	0.4231
CT	0.5	0.4375
Cr	1/3	0.4303
Cs	0.387	0.486

Figure 4 is a block diagram for a traffic light control system with three phases. It is for a junction with three arms. The traffic light detectors inform the queue of vehicles to the control system. This information determines the green signal time interval on the corresponding arm. At least the adaptive traffic light components are detectors, amplifiers, timer modules, drivers, seven segments, and signals. Arduino ATmega2560 is the microcontroller that acts as brain control.

3.4. Discussion

The phase order of the adaptive traffic lights depends on the apparent demand at the T-junction. The order may change in each traffic light cycle. It may consist of three-phase or two-phase traffic lights. The coverable states of each phase of the model are satisfied. It indicates that the model is correct because it satisfies all the properties. There are six possibilities for the sequence of the adaptive traffic lights while implementing three phases and the sequence when active in two phases. The traffic lights keep green on the phase west only when there is no vehicle queue. It is assumed to be the T-junction initial phase of the traffic light cycle.

It uses phase west as the initial. There are two possibilities for the sequence of traffic lights using three phases. They are i) Phase West – Phase North – Phase East and ii) Phase West – Phase East – Phase North. Two possibilities for the sequence of traffic lights using two phases are i) Phase West – Phase North and ii) Phase West – Phase East.

The traffic light phase cannot repeat the same phase directly. For example, after one cycle of west phase traffic lights, it is only allowed to repeat the west phase by scheduling the other traffic light phase first. The next phase may be the northern, eastern, or both sequentially.

On the schedule for an adaptive traffic light, there are three green signal durations, namely 15 seconds, 19 seconds, or 23 seconds. It uses 23 seconds of the green signal when there is heavy traffic, 19 seconds when there is medium traffic and 15 seconds when traffic is low. Settings 23 seconds of the green signal is the maximum duration, and 15 seconds is the minimum duration. The time in between is 19 seconds. It can increase to the maximum green signal duration while it is required. It adjusts to the volume of traffic flow. The control system automatically determines the duration of the green signal. It depends on the installed vehicle sensor information of the existing vehicle queue.

Table 2 shows the three phases of adaptive traffic lights. The vehicles on the west arm wish to go east arm, and the north arm wants to go west arm medium. The vehicles wish to go north in low traffic at the east arm. Table 3 presents the implementation of two traffic light phases due to the north traffic lights phase being ignored.

Table 2. The signals schedule when low east traffic and medium for west and north traffic

Phase	Green	Inter Green Yellow	Inter Green All Red	Red	Cycle
		(Seconds)			
West	19	3	3	49	71
East	15	3	3	53	71
North	19	3	3	49	71

Table 3. The signal schedule for the phase west and east

Phase	Green	Inter Green Yellow	Inter Green All Red	Red	Cycle
		(Seconds)			
West	19	3	3	28	50
East	19	3	3	28	50

Based on the flowchart in Figure 5, when the traffic volume is low, the time interval for the green signal is 15 seconds. While the traffic volume is medium, the time interval for the green signal is 19 seconds. If the traffic is heavy, the time interval for the green signal is 23 seconds. If there is no queue of vehicles on a junction arm, then the traffic phase is not scheduled. During the queue of vehicles from west to east, vehicles from the north will go west, and vehicles from the east will go north empty, then the north traffic light turns red, and the signals for the west and east arms turn green.

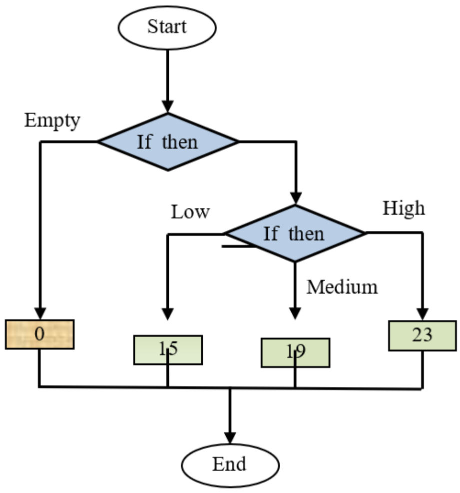

Figure 5. Green time intervals using adaptive traffic lights

The structural complexity presented in Table 1 is calculated based on the formula by Taiping and Peisi [27], [28]. The structural complexity of the adaptive traffic light is 25% higher than systems implementing a fixed-time strategy. It generalizes that the investment, installation, and maintenance also increased by 25%. Thus, advanced techniques are more expensive than simple ones. However, the increase in costs can be categorized as realistic.

Adaptive traffic lights are the ideal system. The complexity of the structure is close to 0.5. There are many experts in the field of automation now. It is a perfect situation. They have a lot of knowledge about adaptive traffic light control systems. Authorities need not worry about systems requiring maintenance. It is optional to bring expensive experts from abroad. Likewise, investment and installation increased by 25%. Domestic experts have been able to solve this problem.

The safety, comfort, and efficiency of travel outweigh the cost increase. It means that an automatic system, namely an adaptive traffic light is feasible. It is ideal to be applied at the T-junction studied. The duration of a traffic light cycle changes according to demand. According to Cahyono [4], adaptive traffic lights can reduce travel delay rather than a fixed time strategy while the traffic fluctuates. Therefore, it is expected that T-junction performance will improve. However, it also needs to be added for security equipment and possible acts of vandalism.

There are many similar T-junctions to the toll road gate, as shown in Figure 6. In addition, traffic light settings can be applied to an adaptive system. As a result, road users are safe and comfortable. Moreover, the travel time is efficient. There are many advantages to adaptive traffic lights implemented. It can reduce travel delays and keep road users safe. Additional equipment for adaptive traffic lights, namely vehicle detectors and seven segments. The routine yearly maintenance and equipment security is around 10% of the initial investment cost. Therefore, it is low and manageable. There are many local experts for installation and routine maintenance.

Traffic lights are better equipped with yesterday's data learning capabilities for predicting a daily increase or decrease in vehicle volume, such as approaching an Eid holiday. The input consists of the queue and time (day or night).

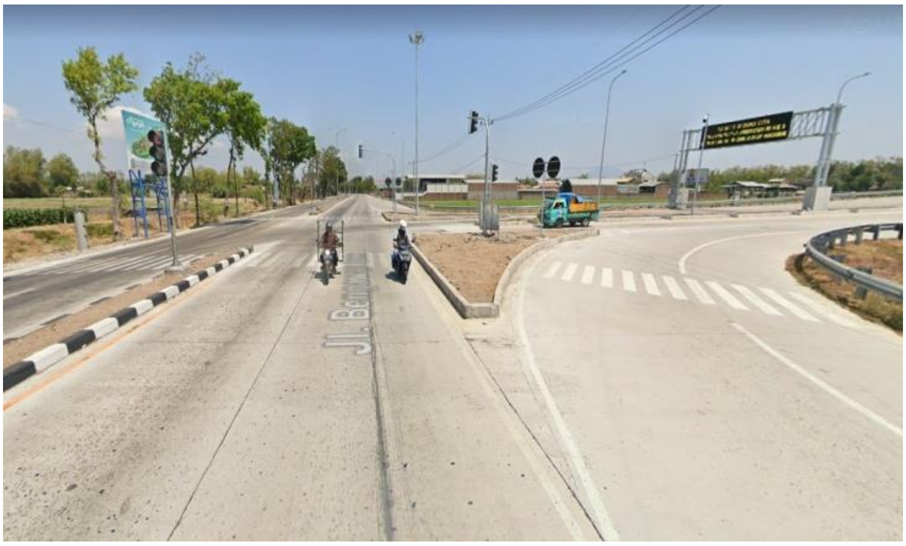

Figure 6. The T-junction of toll road gate [29]

4. CONCLUSION

The adaptive traffic lights time strategy is feasible. It is a manifestation of an advanced safety travel management system for road users. Travel time is efficient and comfortable because the delay is low. Traffic lights can adjust to the demand of vehicles queuing. Traffic light systems using a fixed-time strategy are safe but inefficient due to high delays. The control system's adaptive traffic light's structural complexity is 25% higher than systems implementing a fixed-time strategy. The structural complexity of the adaptive traffic light is feasible. The advanced system needs the installation budget, maintenance costs, the number of local experts capable of handling advanced systems, security equipment, and possible vandalism acts. It is all doable and manageable.

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REFERENCES

[1] *Peraturan Pemerintah Republik Indonesia Nomor 15 Tahun 2005*, No. 15. Republik Indonesia, 2005.

[2] Ofyar Z. Tamin, *Perencanaan, pemodelan and rekayasa transportasi*. ITB, 1997.

[3] B. Yulianto, "Traffic signal controller for mixed traffic conditions," *IOSR Journal of Mechanical and Civil Engineering*, vol. 4, no. 1, pp. 18–26, 2012, doi: 10.9790/1684-0411826.

[4] S. Daru Cahyono, D. Sutomo, S. Aji, D. Sudarno, P. Utomo, and T. Tristono, "Modification of the Norwegian traffic light states as the method to reduce the travel delay," *Computer Science and Information Technology*, vol. 7, no. 1, pp. 22–30, Jan. 2019, doi: 10.13189/csit.2019.070102.

[5] F. Kurniawan, H. Sajati, and O. Dinaryanto, "Adaptive traffic controller based on pre-timed system," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 14, no. 1, pp. 56–63, Mar. 2016, doi: 10.12928/telkomnika.v14i1.2798.

[6] M. Suhairi, "Pengurangan kompleksitas komputasi pada multiview HEVC berbasis perangkat FPGA." Institut Teknologi Sepuluh Nopember, 2018.

[7] "Kamus Besar Bahasa Indonesia (Great Dictionary of the Indonesian Language)."

[8] S. D. Cahyono, T. Tristono, S. Aji, and P. Utomo, "Determining travel delay of vehicles queue at a traffic signal," *BAREKENG: Jurnal Ilmu Matematika dan Terapan*, vol. 14, no. 3, pp. 321–332, Sep. 2020, doi: 10.30598/barekengvol14iss3pp321-332.

[9] T. Tristono and M. Sidqon, "Simulasi rute alternatif berbasis asal dan tujuan perjalanan untuk mengurai kemacetan," *Al-Khwarizmi: Jurnal Pendidikan Matematika dan Ilmu Pengetahuan Alam*, vol. 3, no. 1, pp. 93–106, Sep. 2018, doi: 10.24256/jpmipa.v3i1.221.

[10] D. Hartanti, R. N. Aziza, and P. C. Siswipraptini, "Optimization of smart traffic lights to prevent traffic congestion using fuzzy logic," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 17, no. 1, pp. 320–327, Feb. 2019, doi: 10.12928/telkomnika.v17i1.10129.

[11] N. E. Mohamed and I. I. Radwan, "Traffic light control design approaches: a systematic literature review," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 5, pp. 5355–5363, Oct. 2022, doi: 10.11591/ijece.v12i5.pp5355-5363.

[12] E. I. Abdul Kareem and H. K. Hoomod, "Integrated tripartite modules for intelligent traffic light system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 3, pp. 2971–2985, Jun. 2022, doi: 10.11591/ijece.v12i3.pp2971-2985.

[13] Y. Sabri and N. El Kamoun, "Traffic management in vehicular adhoc networks using hybrid deep neural networks and mobile agents," *IAES International Journal of Artificial Intelligence (IJ-AI)*, vol. 12, no. 1, pp. 114–123, 2023, doi: 10.11591/ijai.v12.i1.pp114-123.

[14] Desmira, M. A. Hamid, N. A. Bakar, M. Nurtanto, and Sunardi, "A smart traffic light using a microcontroller based on the fuzzy logic," *IAES International Journal of Artificial Intelligence*, vol. 11, no. 3, pp. 809–818, 2022, doi: 10.11591/ijai.v11.i3.pp809-818.

[15] Y.-S. Huang and T.-H. Chung, "Modelling and analysis of air traffic control systems using hierarchical timed coloured Petri nets," *Transactions of the Institute of Measurement and Control*, vol. 33, no. 1, pp. 30–49, Feb. 2011, doi: 10.1177/0142331208095623.

[16] Y.-S. Huang, Y.-S. Weng, and M. Zhou, "Design of regulatory traffic light control systems with synchronized timed petri nets," *Asian Journal of Control*, vol. 20, no. 1, pp. 174–185, Jan. 2018, doi: 10.1002/asjc.1536.

[17] Y. A. Messah, "Kajian penerapan rekayasa lalu lintas sistem satu arah pada simpang tiga straat a Kota Kupang," *Teknik Sipil*, vol. 4, no. 2, pp. 217–230, 2015.

[18] B. Septiani, P. Semuel, Y. R. Rompis, and S. V Pandey, "Studi pemanfaatan lampu lalu lintas untuk penyeberang jalan dan pengaruhnya terhadap panjang antrian kendaraan (Studi kasus: Pelican depan manado town square)," *Jurnal Sipil Statik*, vol. 5, no. 2, pp. 67–82, 2017.

[19] A. Machdani, S. Attamimi, and B. Husodo, "Sistem kontrol lampu lalu lintas untuk layanan darurat berbasis internet of things (IoT)," *Jurnal Teknologi Elektro*, vol. 10, no. 3, Feb. 2020, doi: 10.22441/jte.v10i3.007.

[20] T. Pangemanan and A. Rondonuwu, "Perancangan sistem kontrol lampu lalu lintas cerdas dengan menggunakan mikrokontroler dan kamera," *Jurnal MIPA*, vol. 8, no. 3, Oct. 2019, doi: 10.35799/jmuo.8.3.2019.26198.

[21] G. L. Djavendra, S. Aisyah, and E. R. Jamzuri, "Desain sistem pengatur lampu lalu lintas dengan identifikasi kepadatan kendaraan menggunakan metode subtraction," *JURNAL NASIONAL TEKNIK ELEKTRO*, vol. 7, no. 2, Jul. 2018, doi: 10.25077/jnte.v7n2.541.2018.

[22] A. Wibowo, K. Wijayanti, and R. Budhiati Veronica, "Penerapan aljabar max-plus pada pengaturan sistem antrian traffic light," *UNNES Journal of Mathematics*, vol. 7, no. 2, pp. 195–205, 2018.

[23] B. Barzegar, M. Mehrabanian, S. Bandegan, and S. Bandegan, "Fuzzy logic for a traffic signal control with colored petri net," *Australian Journal of Basic and Applied Sciences*, vol. 5, no. 12, pp. 2961–2964, 2011.

[24] O. Yaqub and L. Li, "Modeling and analysis of connected traffic intersections based on modified binary petri nets," *International Journal of Vehicular Technology*, vol. 2013, pp. 1–10, Apr. 2013, doi: 10.1155/2013/192516.

[25] Y. An, N. Wu, X. Zhao, X. Li, and P. Chen, "Hierarchical colored petri nets for modeling and analysis of transit signal priority control systems," *Applied Sciences*, vol. 8, no. 1, Jan. 2018, doi: 10.3390/app8010141.

[26] D. Adzkiya, "Membangun model petri net lampu lalulintas dan simulasinya," Institut Teknologi Sepuluh November, 2008.

[27] M. Taiping and Z. Peisi, "Modeling and performance analysis of manufacturing execution system based on petri net," *The Open Cybernetics and Systemics Journal*, vol. 9, no. 1, pp. 1350–1357, Sep. 2015, doi: 10.2174/1874110X01509011350.

[28] T. Tristono, S. D. Cahyono, Sutomo, and P. Utomo, "Investigate the complexity of the control system of the Norwegian traffic light using Petri net model," *Journal of Physics: Conference Series*, vol. 1211, no. 1, Apr. 2019, doi: 10.1088/1742-6596/1211/1/012022.

[29] Google Map, "T-junction of toll road gate." Accessed February 21, 2021 [Online]. Available: https://www.google.com/maps.

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