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Modeling and simulation of queue waiting time at traffic light intersection

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Abstract. Long queues of vehicles are often found at various traffic light intersection in cities. Such situation is caused by many factors, including the duration of traffic lights that do not match with the arrival of the vehicles. In this article, we propose a model of queue at a road intersection with traffic lights where it can be determine the appropriate traffic light duration based on the arrival of the vehicle, so that the queue waiting time can be obtained that is as far as possible under the driver's time stress threshold. The waiting time in the queue is very dependent on the accuracy of the traffic light time duration setting, both red and green lights on all intersection lines. The research method that will be carried out is firstly to determine the vehicle waiting time model in the queue at the red light phase, followed by the waiting time model in the green light phase with the arrivals by Poisson process with M/M/1 queuing model, then, the waiting time of all vehicles will be determined in one traffic light cycle. Through the implementation of the queue waiting time model, it is expected to obtain an average waiting time for each of vehicle, based on the arrival process and the duration time of traffic lights. The application of SimEvents MATLAB-Simulink is used to demonstrate the calculation from the model that being built for the queue waiting time.

1. Introduction

The number of vehicles in major cities in Indonesia is increasing every year. This is not proportional to the availability of street capacity which results in traffic congestion in various places. On the other hand, the existing traffic management has not been optimal, in addition to the chaos of traffic. An effective solution is needed to solve the traffic congestion problems. One of solution is by improving the traffic light management at the intersection. Traffic lights are generally used to manage traffic in each lane to move in rotation so that traffic congestions can be avoided [1, 2]. However, problems often arise when the setting the traffic time duration is not optimal that causes a long queue of vehicles. Therefore, a proper waiting time model is needed to be applied to the traffic light traffic control so as not to increase the number of queues.

In this paper, we proposed a modelling and simulation, specifically about the waiting time of vehicles in the queue of the traffic light intersection, so that it can be observed and analysed. A scenario can be made to determine the exact duration time of the traffic lights in each path, so that the long queues of vehicles that occur can be decomposed. Vehicles can immediately pass through the intersection so that congestion can be avoided. In a previous study, a LINTAS simulator design was developed to simulate the traffic system in Bandung, Indonesia [3, 4].

The model produced in this paper is expected to be applied to determine the exact time duration of the traffic light in one cycle, to be applied at the various location of the very dense road with the traffic light intersections in Bandung City. One traffic light cycle is the duration of time from the red to the green light. The vehicle arrival pattern used in this paper is a Poisson process, with any services are exponentially distributed [5-8]. The Research related to the modeling of waiting time at traffic intersections, discusses the solution for vehicle waiting time at a traffic light intersection with the distribution of the arrival of Compound Poisson [9-11]. The other researchers have examined the traffic intersection based on several methods such as modelling [1, 10] and fuzzy inference systems [2].

The benefits of the proposed modelling and simulation are for monitoring and predicting congestion at intersections, as well as possible solutions that can be taken to solve the congestion problems at each of intersection paths. The simulation are built by computer application, where in current time, there are many computer application systems in various fields. Apart from in the field of transportation, computer applications are also used in the field of education, for example the use of Geogebra applications [12, 13] or the implementation of computer based tests [14]. The novelty described in this paper compared to the previous similar research is about the implementation of the model that being built, where the MATLAB-Simulink SimEvents application is used to find the value of vehicle waiting time at traffic light intersections, and also other parameters that needed.

2. Method

In this article, we analyse the queue waiting time at traffic light intersection by modelling and simulation. The modelling is performed based on queuing theory with the M/M/1 principle, while the simulation which include the design of traffic simulator and its components, is created using the SimEvents MATLAB-Simulink application [15]. The reason for choosing this queueing model is due to M/M/1 is the simplest model and was commonly use [16]. The pattern of vehicles' arrival is random when entering the queue system at the intersection of the red light, and the departure is also random. The departure of the vehicle in a number of lanes flows together at a time when the green light is on. Data on the duration of traffic lights is obtained through observation and literature for the location of one particular traffic junction in the city of Bandung, where the location having quite dense traffic. Another data that collected is the average rate of arrival of vehicles entering the intersection, and the average rate of departure from the intersection.

The SimEvents-MATLAB application has been used as a tool to simulate a system in various fields, including Transportation [3, 4] and Internet [17, 18] which involves data flow methods on Content Delivery Networks (CDN) technology and Service-oriented Routers [19-23]. Several methods can be used in vehicle distribution simulations, including load balancing [24] as well as artificial intelligence Bayesian networks [25, 26]. Besides SimEvents, another simulator that is commonly used is ns3 [27]. The components of the simulator system using SimEvents are modules in the form of an entity generator as a medium for generating entity (vehicles), server modules as media services, gate modules as representations of traffic intersections, links as representations of transportation routes, and sink modules for entity disposal.

3. Modeling

3.1. Queuing Theory and Poisson Process

The queue system can be described as the arrival of customers for a service, waiting to get service and leave the system after receiving service. Arrival pattern is one of the basic elements that must be considered by service providers. The customer arrival pattern can be seen from the interarrival time between the arrival of two customers which can be deterministic or stochastic. The arrival pattern is deterministic if the arrival pattern is fixed/unchanged and interarrival time can be determined. Besides that the deterministic customer arrival pattern also produces a pattern of fixed queue lengths as well. Meanwhile, the arrival pattern is stochastic, its arrival has not been determined so it needs to find its

suitability with a particular distribution. With an uncertain arrival pattern that changes according to time, the queue length does not have a pattern in the queue.

Services in the queue can also be single or batch. In general, customers are served for a certain time by a specified server, but in some situations customers are served simultaneously by the same server. The service process may depend on the number of customers waiting to be served. If there is a long queue, the server must be able to work faster, otherwise if the server cannot work fast, there will be a queue buildup and it will be inefficient. There are several forms of queue discipline. Among them is a service that is quite well known and easily found every day is First Come First Serve (FCFS), meaning that customers are served based on the order of arrival, the more ahead will be served first.

Poisson process is one of the most important models used in queueing theory. Poisson process represent discrete arrivals such as calls, packets, etc., which often called as entity. Poisson can be explained as a process that produces values for a random variable in the number of experiments that occur over a period of time. For example, the process of vehicle arrival at a road in one minute, vehicle arrival in one hour or other time. Mathematically the Poisson process is stated by $N(t)$ which describes the number of arrivals that have occurred in the interval $(0, t)$ as depicted in Figure 3.1.
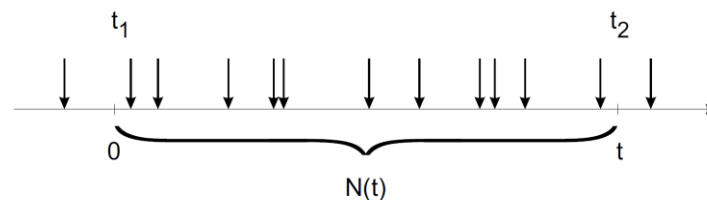

Figure 3.1. Poisson process

The number of arrivals $N(t)$ in a finite interval of length t obeys the Poisson λt distribution, formulated by

$$P\{N(t) = n\} = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{3.1}$$

Where $P\{N(t) = n\}$ is the probability of the arrival, λ is the arrival-rate, $N(t) = n$ is the n number of arrival at time t.

Poisson distribution is a discrete distribution that has an average value equal to its variance. An interesting feature of the Poisson process is that if the arrivals number of entity per time is to follow a Poisson distribution with an average arrival rate λ, then the interarrival time will follow an exponential distribution with average of $1/\lambda$ [7].

3.2. Traffic Light Model

Traffic lights play an important role in the infrastructure of cities and all cities in the world. In traffic regulation, the effect on the smooth flow of traffic is the number of vehicle arrivals, the number of vehicles waiting in line and the length of vehicles at the intersection. Waiting at the intersection is an inevitable disorder every day. In Mathematics, the basic problem of traffic theory is to get the expected waiting time for each vehicle at a traffic light intersection [2, 9].

In this paper, we discuss the basic concepts in modeling vehicle waiting time in a queue at traffic light intersections at a certain deterministic time duration. In this concept there are several things that must be considered, namely: 1) at the beginning of the green light phase, all vehicles in the queue begin to move leaving the queue; 2) the uniformity of the average pattern of vehicle arrival during a cycle, where the arrival pattern does not depend on time; 3. the uniformity of the vehicle departure pattern when leaving the queue; 4) arrival of vehicles not exceeding its capacity which is determined by the maximum number of vehicles in the queue.

Figure 3.2 illustrates the process of waiting time for all vehicles at a traffic light intersection. The waiting time of each vehicle at the traffic intersection is the total waiting time of all vehicles divided by the total arrivals per cycle. To model the time of the vehicle at a traffic intersection, it is assumed that: 1) the arrival pattern follows the Poisson process; 2) arrival of vehicles from one direction; 3) there is no turning lane at the intersection; 4) vehicles cannot get out of the queue; 5) vehicle acceleration and deceleration is ignored when turning at an intersection or stopping due to a red light; 6) the queue process follows the First Come First Serve (FCFS) discipline.

Some factors that affect the waiting time of vehicles in the queue at the traffic light intersection are: 1) the length of time the red light lights up, notated R; 2) duration of one traffic light cycle, notated T; 3) the number of vehicles entering the queue at the time t is denoted $N(t)$; 4) queue length at t, denoted $Q(t)$.
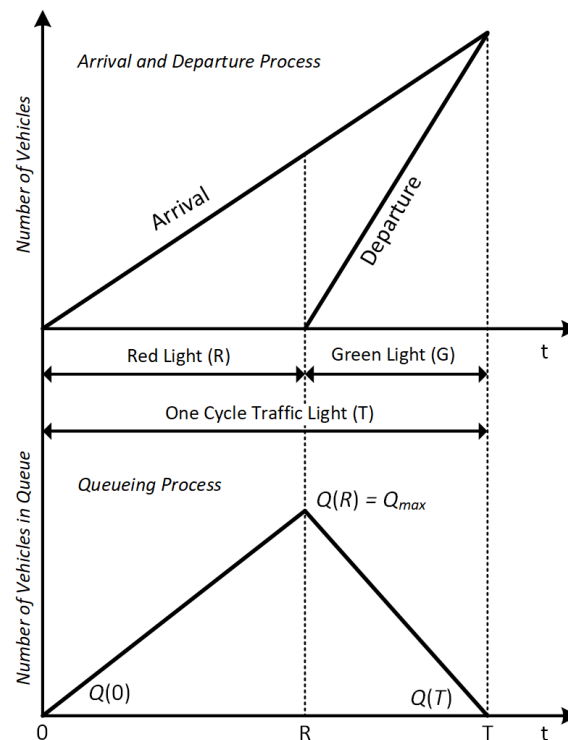

Figure 3.2. Vehicle waiting time model at a traffic light intersection

The situation of a vehicle in a queue at a traffic light intersection is expected to meet conditions such as Figure 3.3., Where the number of vehicles in the $0 \leq t \leq T$ interval at the queue at a traffic light intersection is affected by time t. The time interval $0 \leq t \leq T$ is divided into two phases, namely the red light phase at $0 \leq t \leq R$ intervals and the green light phase at the $R \leq t \leq T$ interval.
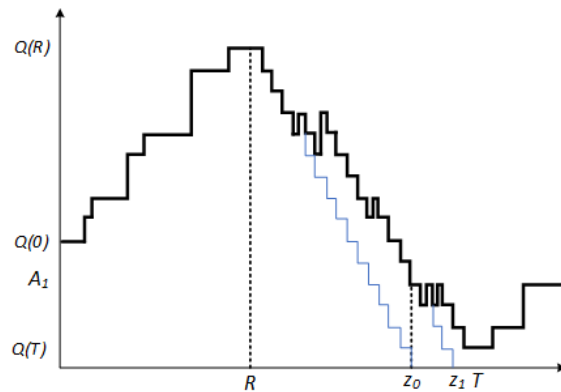
Figure 3.3. The process of queuing in one cycle [1]

In the red light phase interval $0 \leq t \leq R$, when $t = 0$, the number of vehicles in the queue is the remaining queue from the previous cycle, $Q(0)$. Next, the number of vehicles in the traffic queue is denoted by $Q(t)$. The $Q(t)$ function will increase gradually based on the addition of the vehicle coming into the queue, $N(t)$. The number of vehicles will reach the maximum at the end of the red light phase which is notated with $Q(R)$.

In the green light phase that is at the $R \leq t \leq T$ interval, when $t = R$, all vehicles in the queue, start moving leaving the queue at the intersection of traffic lights. Based on assumptions, the model will be discussed using first come first serve (FCFS) queue discipline. Which means, the leading vehicles will exit the queue first followed by the vehicles behind it. In the green light phase, the number of vehicles leaving the queue, in an ideal situation, must be more than the number of vehicles entering the queue so that the number of vehicles in the queue as much as $Q(R)$ will continue to decrease until the end of the green light phase. At the end of the green light phase, which is when $t = T$, it is expected that the number of vehicles remaining in the traffic light queue is not more than the number of previous vehicles, or in other words $Q(t) \leq Q(0)$.

Suppose that λ is the arrival-rate of vehicles entering the queue at the traffic light intersection stated by vehicle per second. Meanwhile, μ is the departure-rate of the vehicle leaving the queue stated by vehicle per second.

Based on the Figure 3.3, in a traffic light cycle, the total waiting time required by the vehicle is affected by the number of vehicles in the queue at the traffic light intersection. L states as the total waiting time of all vehicles at the traffic light intersection, obtained by integrating the $Q(t)$ curve at $0 \leq t \leq T$ intervals using the Riemann integral as follows:

$$L = \int_0^T Q(t) \, dt \tag{3.2}$$

Based on the integral nature of the summing properties of the interval, the $0 \leq t \leq T$ interval can be divided into two intervals, namely $0 \leq t \leq R$ for the red light phase (L_1), and $R \leq t \leq T$ for the green light phase (L_2). Equation (3.1) can be written as follows:

$$L = L_1 + L_2 = \int_0^R Q(t) \, dt + \int_R^T Q(t) \, dt \tag{3.3}$$

Next, each phase of the traffic light will be explained.

3.3. Red Light Phase
At the red light phase, the number of vehicles in the queue at time t is denoted by $Q(t)$ with the following conditions:

a. $Q(0)$ is the number of vehicles at $t = 0$ in the queue at the traffic light intersection which is the remaining queue from the previous cycle.
b. $N(t)$ is the number of vehicles entering the queue at the traffic light intersection at time t.

Thus, based on the above provisions, $Q(t)$ in the red light phase can be defined as follows:

$$Q(t) = Q(0) + N(t)$$

So, during the red light phase, the total waiting time required for all vehicles while in the queue at the traffic light intersection is:

$$L_1 = \int_0^R Q(0) + N(t)\, dt$$

It is assumed that $N(t)$ has a Poisson process, so that according to the probability function in equation (2.1), we obtain

$$E[N(t)] = \lambda t$$

Thus, the expectation value of L_1 can be obtained

$$E[L_1] = E\left[\int_0^R Q(0) + N(t)\, dt\right] = E[Q(0)]R + \tfrac{1}{2}R^2\lambda \tag{3.4}$$

as the total waiting time of all vehicles in the red light phase. After passing through the red light phase, the vehicle in line at the intersection starts moving into the green light phase which is the final phase in one cycle.

3.4. Green Light Phase

In phase of the green light, the service is carried out on vehicles in the traffic light intersection where the vehicle in the previous queue comes out first followed by other vehicles. In addition to the vehicles that came out, on the other hand, there were new vehicles entering the queue. Therefore, at the interval $R \leq t \leq T$, the number of vehicles in the queue is influenced by three factors: 1) the maximum number of vehicles in the red light phase; 2) the number of new vehicles entering the queue; 3) the number of vehicles leaving the queue. The number of vehicles leaving the queue system is assumed to be a fixed amount, not affected by the number of vehicles in the queue, called as stationary system.

The number of vehicles in the queue at time t is denoted by $Q(t)$, where in the initial phase of the green light, the number of vehicles in the queue is assumed to be $Q(R)$. The average service time when the vehicle leaves the queuing system is $1/\mu$. The number of vehicles entering the queue system in the green light phase is A_n. Furthermore, the model of vehicle's queue waiting time at the traffic light intersection will be calculated, where based on equation (3.2), the total waiting time for one cycle is the total number of vehicle waiting times in the red light phase (L_1) and the total waiting time of the vehicle at green light phase (L_2), formulated with

$$E[L] = E[L_1] + E[L_2] = \left(E[Q(0)]R + \tfrac{1}{2}R^2\lambda\right) + E\left[\int_R^T Q(t)\, dt\right]$$

The total waiting time of the vehicle in the green light phase is affected by the arrival and departure of the vehicle, where to determine L_2, first $Q(t)$ will be calculated at the interval (R, T). Next, define $Q_1(t)$ which is identical to $Q(t)$ at interval (T, ∞) and (R, ∞), such that

$$L_2 = \int_R^T Q(t)\, dt = \int_R^\infty Q_1(t)\, dt - \int_T^\infty Q_1(t)\, dt$$

Next, at time interval (R, ∞), let $A_1, A_2, \dots, A_n$ is the number of vehicle arrivals at intervals $R \leq t \leq R + \frac{1}{\mu}Q(R)$, $R + \frac{1}{\mu}Q(R) \leq t \leq R + \frac{1}{\mu}(Q(R) + A_1)$, $\dots$, $R + \frac{1}{\mu}(Q(R) + A_{n-2}) \leq t \leq R + \frac{1}{\mu}(Q(R) + A_{n-1})$. Then, let $Z_0 = R + \frac{1}{\mu}Q(R)$, $Z_1 = Z_0 + \frac{1}{\mu}A_1$, $\dots$, $Z_n = Z_{n-1} + \frac{1}{\mu}(A_1 + \cdots + A_n)$, such that (3.12) can be written as follows:

$$L_2 = \left[\int_R^{Z_0} Q_1(t)\, dt + \sum_{n=0}^{\infty} \int_{Z_n}^{Z_{n+1}} Q_1(t)\, dt \right] - \left[\int_T^{Z_0} Q_1(t)\, dt + \sum_{n=0}^{\infty} \int_{Z_n}^{Z_{n+1}} Q_1(t)\, dt \right]$$

Use expectation properties and other mathematical calculation in [10, 11], we have the total waiting time of all vehicles in the phase of green light is as follows:

$$E[L_2] = \frac{1}{2}\mu_1(1-\rho)^{-2}\{(1)(\lambda R) + (1-\rho)(2\lambda R E[Q(0)] + \lambda^2 R^2 + \lambda R I)\} \tag{3.5}$$

where $\rho = \lambda/\mu$, and I is the dividing result of the variance in the number of vehicle arrivals with the average number of vehicles per cycle, formulated by

$$I = \frac{\mathrm{var}\, N(T)}{\lambda T}$$

Next, the total waiting time of all vehicles in the queue in one cycle will be calculated. Based on equation (3.2), (3.3), and (3.7), and refer to [10, 11] , we obtain:

$$E[L] = E[L_1] + E[L_2]$$

$$E[L] = \frac{\lambda R}{2(1-\rho)}\left\{ E[Q(0)] + R + \frac{1}{\mu}\left(1 + \frac{I}{1-\rho}\right) \right\} \tag{3.6}$$

The total waiting time of each vehicle (d) is the result for the total waiting time of all vehicles in queue $(E[L])$ in equation (3.8) with the average arrival of the vehicle into the queue during one cycle $(E[N(T)]) = \lambda T$, formulated by

$$d = \frac{E[L]}{E[N(T)]}$$

$$= \frac{R}{2T(1-\rho)}\left\{ \frac{2}{\lambda}E[Q(0)] + R + \frac{1}{\mu}\left(1 + \frac{I}{1-\rho}\right) \right\} \tag{3.7}$$
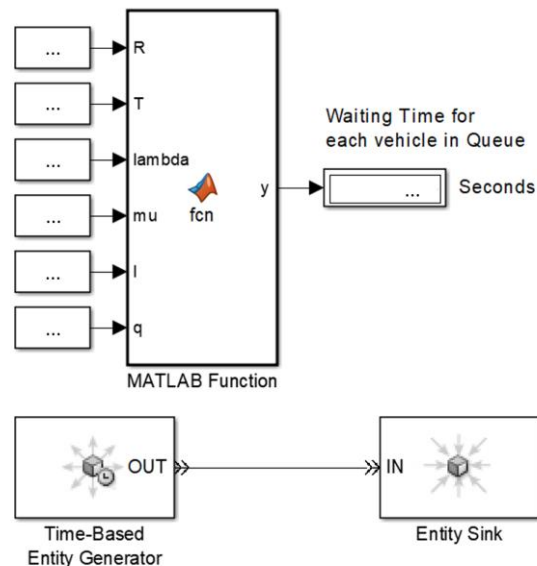
Where the explanation for each variable in equation 3.9 is described in Table 1.

Table 1. Variable Waiting Time for Each Vehicle in Queue

Variable Name	Explanation	Unit
d	Waiting time for each vehicle in the queue	Seconds
T	The time taken turns on the red light to the green light (one cycle)	Seconds
$E[L]$	Total waiting time for all vehicles in queue for one cycle	Seconds
$E[N(T)]$	The average number of vehicles entering the queue system for one cycle	Vehicles
$E[L_1]$	The total time of all vehicles in queue at the red light phase	Seconds
$E[L_2]$	The total time of all vehicles in queue at the red light phase	Seconds
$Q(0)$	The number of vehicles that remains in the previous cycle	Vehicles
R	The total time for the red light phase	Seconds
λ	Average vehicle arrival-rate to the queue	Vehicle per second
$Q(t)$	The number of vehicles in queue, at time t	Vehicles
μ	The average departure-rate of vehicle exits the queue	Vehicle per second
ρ	System utility (λ/μ)	-
I	Comparison of variance of vehicle arrival with average vehicle arrival in one cycle	-

4.   Simulation

The next step is the simulation of the implementation about the model that has been constructed as shown in equation (3.9) using the simulator design depicted in Figure 3.4.

Figure 4.1. The Simulation Application for Traffic Light Intersection

The variable values that will be implemented are obtained based on the data at the intersection of the Soekarno-Hatta - Kiara Condong (Ibrahim Adjie), specifically on the road from east to west as shown in Figure 3.5. The traffic light data for the Soekarno-Hatta - Kiara Condong intersection is described in Table 2.
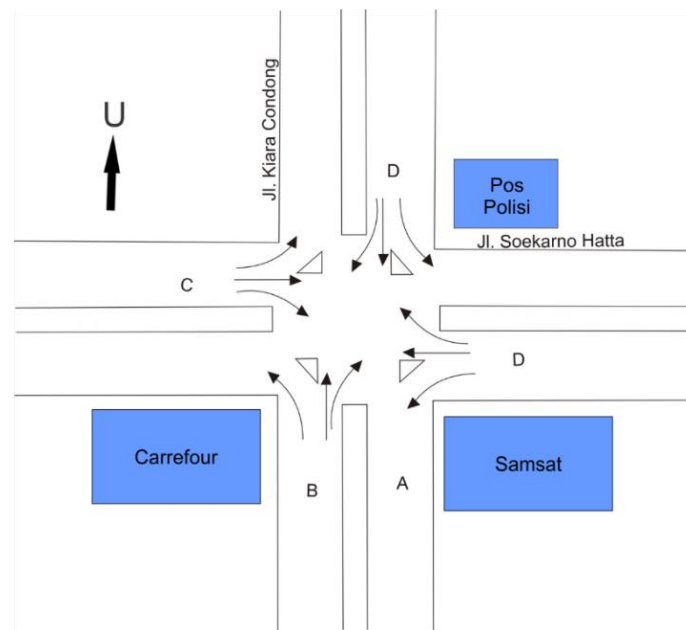
Figure 4.2. The map of intersection at Soekarno Hatta – Kiara Condong

Table 2. The duration time of traffic light at intersection: Soekarno Hatta – Kiara Condong
Phase number = 4; Cycle tim in one phase = 253 Seconds

Red Light Time	Yellow Light Time	Green Light Time
A = 153 seconds	A = 10 seconds	A = 90 seconds
B = 153 seconds	B = 10 seconds	B = 90 seconds
C = 153 seconds	C = 10 seconds	C = 90 seconds
D = 153 seconds	D = 10 seconds	D = 90 seconds

Source: Department of Perhubungan Bandung City [28]

The intersection of Soekarno-Hatta - Kiara Condong is one of the crowded intersections and have a long queue of vehicles. Drivers have to wait long to be free from the queue. Data for each variable in the model that will be applied to the simulator are listed in Table 3.

Table 3. Data for each variable at the intersection of Soekarno-Hatta - Kiara Condong

Variable	Value	Unit	Information
T	253	Seconds	The time taken turns on the red light to the green light (one cycle)
$Q(0)$	40	Vehicles	The number of vehicles that remains in the previous cycle
R	153	Seconds	The total time for the red light phase
λ	0.67	Vehicle per seconds	Average vehicle arrival-rate to the queue
μ	1.167	Vehicle per seconds	The average departure-rate of vehicle exits the queue
I	1	-	Comparison of variance of vehicle arrival with average vehicle arrival in one cycle

By using the model in equation (3.9) and using the simulator application in Figure 3.4, the waiting time of each vehicle at the intersection is 195.4 seconds.

5. Conclusion

In this paper a waiting time model for vehicles at traffic intersections is analyzed. The model obtained is a model of the vehicle waiting time in the queue for one cycle. SimEvents application is used to calculate the queue waiting time for given parameters. Theoretically, this model can be used at various traffic light intersections to be a solution for the one that cause very long vehicle queues. Modeling the waiting time of the vehicle in the queue at the traffic light intersection is expected to be used to determine the setting of the duration of the red or green traffic lights automatically so that it can avoid the queue that is too long and uneven or unfair at all lanes of the intersection.

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