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Optimization of Traffic Signal Timing at Isolated Intersection using Minimizing Queue Length Method and Lane-area Detectors (E2)

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Abstract **– This study aim to contribute another solution for traffic signal design and optimal signal timing at isolated intersection based on minimizing queue length methods from effective green time and lane-area detectors (E2) from open resource software Sumo. By using real-time simulation model for single intersection in Taiwan associated with finding a suggested effective green time are to minimizing the increase in the number of queuing vehicles, maximizing throughput in one signal cycle and maximum number of vehicles can pass through the intersection without stop. Firstly, this method will find down the suggested effective green time when taking geometry and traffic flow data in the single intersection. Then, building the simulation model for both the single intersection in existing signal timing and suggested signal timing (new cycle length) are to calculate the queuing length in two models. In particular, the suggested effective green time will be detect from linear model. Moreover, the E2 is a tool of Sumo software and explain vast amount of measures such as queuing length, average time loss to compare the different between suggested simulation model and existing simulation model. Finally, this paper will illustrate and conclude the capability of this method and future work.**

Keywords **– Traffic Control, Optimal Signal Timing, Linear Programming, Simulation Model.**

I. INTRODUCTION

Nowadays, the traffic congestion has becoming urgent problem in urban area and transportation in many countries in the world. The truth is that traffic congestion is caused by multiple reasons and typically it has been happening at intersections in rush hour. Traffic signal at intersection exist to keep traffic safe, both for automotive and pedestrian traffic [1]. However, major traffic intersections generally exhibit far more complicated behavior, containing multiple phases, directions of travel, and a large number of lanes. The presence of such elements makes the analysis of major intersection significantly more complex [2]. Thus, traffic signal timing at the intersection is extremely important role to control the transportation as well as decrease traffic jam. Traditionally, Webster's method of traffic signal design is an analytical approach of determining the optimum signal cycle time, corresponding to minimum total delay to all the vehicles at the approach roads of the intersection. However, in case of a saturated traffic flow the Webster method becomes inapplicable because the cycle length becomes unreasonably [3] and the literature on the optimization of traffic signals can be classified into some studies [4]. Almost discussed solutions above typically are to build the fixed- time signals control for the intersection. In the age of computer and cutting- edge technology, it’s really necessary to discover another flexible solution to find the actuated signals instead of fixed- time signal at the intersection based on various reality data from sensors that installed on the street as video detector data (VD), electronic toll collection data (e-Tag) data, etc. This paper will take real data from particular traffic signal data of Chaoma road, Chaogui road intersection in Taiwan associated with the optimal queuing method to find the actuated signal on peak period and then checked the outcome by the traffic simulation model using lane-area detectors (E2) tool in Sumo software.

II. Optimization of Traffic Signal Timing at Chaoma- Chaogui Intersection

A. *Data Collection from the Existing Signalized Chaoma- Chaogui Intersection*

In this paper, the considered Chaoma- Chaogui intersection included four approaches as well as located in Taichung city, Taiwan. This intersection is an extremely important role in Taichung transport network when connecting with some major roads in Taichung city which are Huanzhong road in the Westbound, Liming road in the Eastbound. Moreover, the traffic signal control in this intersection is a necessary function to coordinate the transport in urban areas with a number of public areas, particularly Chaogui Park in the Northbound, Chaoma Sports Center in the Southbound, and Taichung football Field in the Westbound. Thus, exploring the optimum traffic signal is extraordinarily significant to reduce idling vehicles in the peak period from 7.45 am to 8.45 am.

(a) (b) (c)

Fig. 1. Chaoma- Chaogui intersection geometry from left to right: (a) The position in Taiwan, (b) Complex traffic light controlled intersection, (c) video detector image

Traffic geometry in Chaoma includes 2 lanes for both sides the West and the East, Chaogui road consists of 2 lanes in the South as well as 1 lanes in the North. The signal control at the intersection composes two phases, each phase that allows going straight, taking a left turn, and taking a right turn. The fixed-time control of 90- second cycle length was adopted for this intersection, to be more precise see Table 1.

Table 1. The existing traffic signal control at Chaoma- Chaogui Intersection

Intersection	Phase	Morning (units of time in seconds)				Afternoon (units of time in seconds)			
		Green	Yellow (amber)	All red	Cycle	Green	Yellow (amber)	All Red	Cycle
Chaogui, Chaoma, 1, 2, 3, 4, (4)	3, 1	55	3	2	90	55	3	2	90
	4, 2	25	3	2		25	3	2	

The video detector data will be taken into this article in real time in order to calculate the cycle length and suitable effective green time base on the density of vehicles in this intersection.

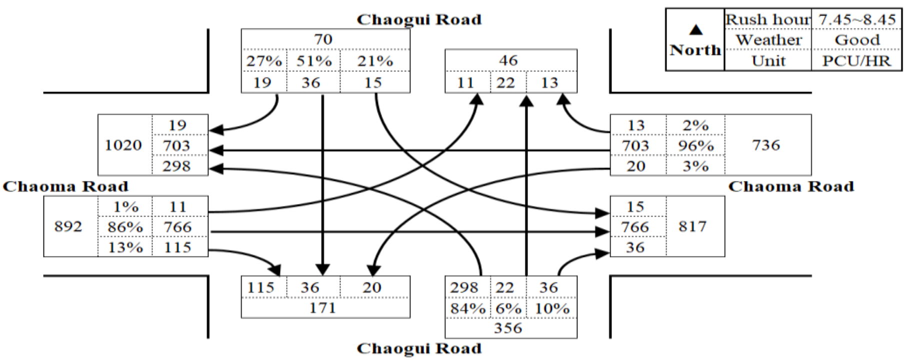


Fig. 2. Passenger Car Unit for each movement in Chaoma- Chaogui Intersection per hour

The complex type of vehicles in this intersection leads to transforming all type of vehicles to PCU (passenger car unit) is necessary. From volumetric data collected by the video detector that included car, motorcycle, bus, truck... the PCU will be calculated for each movement (Fig. 2).

B. *Minimizing Queue Lengths Method*

There are few methods to recognize the optimum value of effective green time when minimizing queue length at the isolated intersection. To be more precise, the first method will base on the departing vehicles and arriving vehicles at a particular intersection [5]. Another one will define the queue lengths for each movement calculated by multiplying the rate of arrival by the corresponding idle time [1]. In this paper, the second method will be concerned. The theory of [1] will build the model to define the minimum value of effective green time and ignore changing red time, amber time, phases and the link of each movement in this intersection.

The model can be built and analyze by some steps: Recognition the existing signal control at the intersection and the real data of traffic flow; Development of the objective function; Identification of constraints; Building the linear programming to find the result; Comparison between result and traditional method.

Firstly, for the recognition purpose in Chaoma-Chaogui intersection, the data from the video detector will be extracted and calculated to the PCU for each movement (Fig. 2) associated with existing traffic control in Chaoma-Chaogui intersection to build the original simulation model (Table. 1). Development of objective function the study multiplied the arrival rate of automobiles traveling in each movement by the duration of the corresponding red time assigned to the affected traffic lanes. The objective function for Chaoma-Chaogui intersection is:

$$Min \sum_1^4 Q_i \tag{1}$$

Where: Q_i: The queuing length in each approach, and four approaches are Q_1, Q_2, Q_3, Q_4, respectively. The existing signal control timing in Chaoma- Chaogui intersection included two phases. Particularly, phase number one will allow the vehicles can pass through this intersection from Westbound to Southbound and vice versa in Chaoma road, we call effective green time for this phase is T1. On this time, all vehicles in the front of the stop-line in the Eastbound and Southbound (in Chaogui road) have to stop because it's the red time for these movements. So the queuing length will be defined for Chaogui road by formula:

$$Q_2 + Q_4 = (GSL+GSS+GSR)\ T1 + (GNL+GNS+GNR)\ T1 \tag{2}$$

Where: T1: the value of effective green time for phase 1; GSL, GSS, GSR, GNL, GNS, GNR: Traffic flow rate (PCU) in Chaogui road (Southbound is “S”, Northbound is “N”), take left-turn (L), go straight (S), take right-turn (L), respectively. By the same manner, when the traffic signal control turned to red light for Chaoma road (M), the effective green time for Chaogui road is T2. The queuing length in Chaoma road will be calculated:

$$Q_1 + Q_3 = (MWL+MWS+MWR)\ T2 + (MEL+MES+MER)\ T2 \tag{3}$$

Where: T2: the value of effective green time for phase 2; MWL, MWS, MWR, MEL, MES, MER: Traffic flow rate (PCU) in Chaoma road (Westbound is “W”, Eastbound is “E”), take left-turn (L), go straight (S), take right-turn (L), respectively. Following (1) the objective function will be defined:

$$\text{Min} \sum_1^4 Q_i = \text{Min}\ [(GSL + GSS + GSR)\ T1 + (GNL + GNS + GNR)\ T1 + (MWL + MWS + MWR)\ T2 + (MEL + MES + MER)\ T2 \tag{4}$$

Then, identification of constraints in traffic control design:

- *Constraints of Pedestrian's Safety:*

$T1 \geq 20.79/vp$ (5)

$T2 \geq 20.85/vp$ (6)

Where: The width of Chaoma road = 20.85(m); The width of Chaogui road = 20.79 (m); vp: is the velocity of pedestrian. The velocity of walking speed of pedestrian in traffic signal design depends on some factors which are age, gender, physical constitution, motivation and purpose of travel, distance to be covered, and weather and terrain conditions [6]. Choosing the appropriate value of pedestrian speed should base on some standards, regions in each country. The net cost of transport reaches a minimum at about 1.05 m/s (3.8 km/h; 2.3 mph) [7]. The U.S. Federal Highway Administration has established an average pedestrian speed of four feet per second (1.2 m/s). In Taiwan, the suggested value of pedestrian speed equals 1 (m/s).

- *Constrains Related to Queue Lengths:*

$Q_3 = (MWL+MWS+MWR)\ T2 \geq 2.a$ (7)

$Q_1 = (MEL+MES+MER)\ T2 \geq 2.a$ (8)

$Q_4 = (GNL+GNS+GNR)\ T1 \geq 1.b$ (9)

$Q_2 = (GSL+GSS+GSR)\ T1 \geq 2.b$ (10)

Where: a and b are the assumption of how many cars can stop in the front of the stop line in each approach to create queue lengths (Chaoma road and Chaogui road). These values can be chosen by the decision maker when concerning the traffic network condition and the traffic capacity of each intersection. In this research, after considering four adjacent intersections with Chaoma- Chaogui intersection the suitable value for a, b equal 11 and 10, respectively.

Fig. 3 The widths of Chaoma road and Chaogui road

Fig. 4 The longest left turn in Chaoma- Chaogui intersection

- *Constraints Related to Vehicle Flow:*

$T1 \geq (30.7+ vl.a)/vv$ (11)

$T2 \geq (31.7+ vl.b)/vv$ (12)

Where: 30.7(m) and 31.7(m): are the longest curve for left turn movement in each phase; a and b: are the values that explained above; vl: is an assumption value the length of a passenger car (vehicle length); vv: is an assumption value the velocity of a passenger car when the traffic light turning to green

The constraints referring to vehicle flow that allows the last vehicle can pass through this intersection on the left turn and right turn movements. Normally, the left turn movement will take time than a right turn. The value of vl in some researches equals from 17 feet to 17.6 feet. The value of vv equals 22 feet/s (about 6.7 m/s) [1] . In this paper, these values will be denoted to build the linear program by Python software. Notice that, each value can be chosen by different designer base on the real traffic situation.

- Building the linear programming by Python software. Firstly, extracting the vehicle arrivals rate (Fig. 2) from video detector data, the passenger car unit per second will be calculated from the passenger car unit per hour. The results recognized: MEL = 0.006 (veh/s), MES = 0.195 ((veh/s), MER = 0.004 (veh/s), MWL = 0.003 (veh/s), MWS = 0.213 (veh/s), MWR = 0.032 (veh/s), GNL = 0.004 (veh/s), GNS = 0.010 (veh/s), GNR = 0.005 (veh/s), GSL = 0.083 (veh/s), GSS = 0.006 (veh/s), GSR = 0.010 (veh/s). Then, defining the objective function followed (4) with variables are optimal values of effective green time, after that inputting all constraints in the model, finally, the result will show the feasible solution area and the optimum solution (Fig. 5 and Fig. 6).

```python
from pulp import *
# Import PCU for each lane in 4 approaches
MEL = 0.006
MES = 0.195
MER = 0.004
MWL = 0.003
MWS = 0.213
MWR = 0.032
GNL = 0.004
GNS = 0.010
GNR = 0.005
GSL = 0.083
GSS = 0.006
GSR = 0.010
# The assumption velocities(speed) of Perdestrians and Vehicles
# 0.3048 is factor to tranform from feet to meter
vp = 1
vv = (22*0.3048)
# The assumption for length of 1 passenger car:
vl = 17*0.3048
# The assumption of how many passenger cars can stop in front of stop line
a = 11
b = 10
# Decision variables_ Effective Green Time
T1 = LpVariable("T1")
T2 = LpVariable("T2")
# Define linear problem_ Objective Function
prob = LpProblem("problem", LpMinimize)
prob += (MWL+MWS+MWR)*T2+MEL+MES+MER)*T2+(GNL+GNS+GNR)*T1+(GSL+GSS+GSR)*T1
# Add All Constrains to model
# 1.The constrains for safety of Perdestrians
prob += T1 >= 20.79/vp       # The width of ChaoGui road = 20.79 (m)
prob += T2 >= 20.85/vp       # The width of ChaoMa road  = 20.85 (m)
# 2.The constrains realated to queueing length
prob += (MWL+MWS+MWR)*T2 <= 2*a
prob += (MEL+MES+MER)*T2 <= 2*a
prob += (GNL+GNS+GNR)*T1 <= 1*b
prob += (GSL+GSS+GSR)*T1 <= 2*b
# 3. The constrains related to traffic flow
prob += T1 >= (30.7+ vl*a)/vv
prob += T2 >= (31.7+ vl*a)/vv
# solve ILP
prob.solve()
# print results
print(LpStatus[prob.status])
print(value(T1))
print(value(T2))
```

Fig. 5. Python code of linear programming

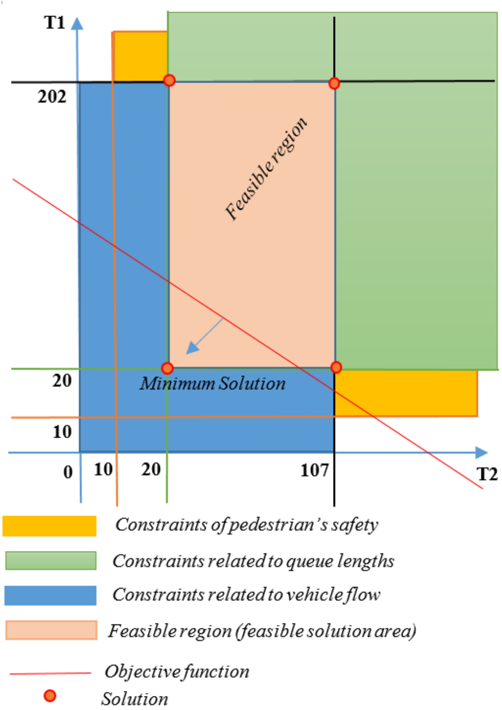


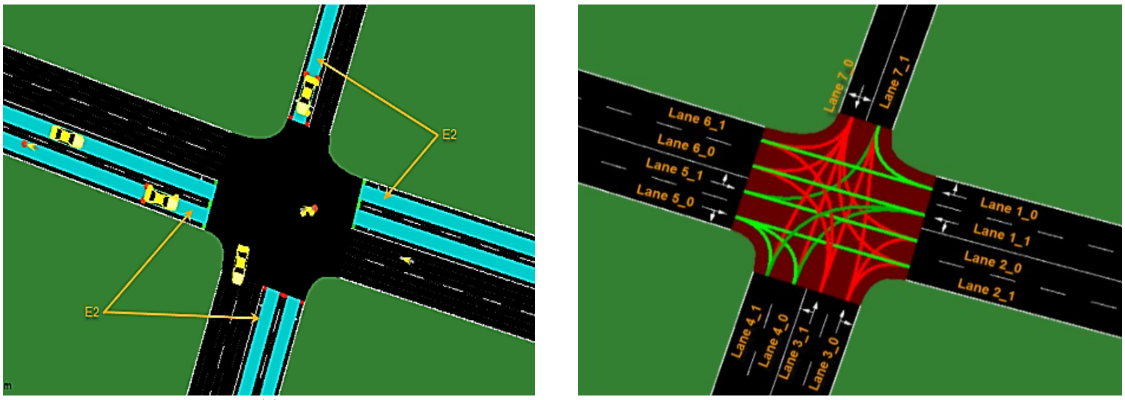
Fig. 6. Feasible solution area

The outcomes of linear programming show the optimal values of effective green time for each phase that could be T1 = 20.79 = 21(s), T2 = 20.98 (s) = 21(s). Compared to existing control signal timing at the intersection, T1 is significantly decreased 24 seconds while T2' s optimum duration slightly decreased 4 seconds. Consequently, the proposed cycle length is 28 seconds shorter than the existing cycle length. Apparently, the values of effective green time T1 = 21 (s) and T2 = 21 (s) are very close to the minimum values of pedestrian' s safety duration ((5) and (6)) these values appear in the feasible solution area (Fig. 6). The reason for this is because the objective function (4) is an increasing function, so the smallest variable value in the feasible solution area will be the optimum solution (Fig. 6).

It seems to be the program has some shortcomings when finding the optimal value of effective green time. Therefore, it's necessary to input more constraints to build a better objective function and better results. On the other hand, the result is an acceptable result to find another solution for designing a traffic signal at an isolated intersection. This study will convince the efficiencies of these results when applying traffic simulation for the original traffic signal and proposed traffic signal based on the Lane-area detector tool (E2) in open resource simulation software named Sumo.

C. *Lane Area Detector (E2) to Capture Traffic Issues at the Intersection*

A lane- area detector (E2) is used to capture traffic on an area along a lane or lanes in Sumo software (Simulation of Urban Mobility). In reality, this would be similar to a vehicle tracking camera. In contrast to an induction loop, a lane-area detector has a certain length which is specified by the length attribute or by the attributes position (pos), and end- position (endPos). The outputs of an E2 Detector are tailored for measuring queues of standing/jammed vehicles and it keeps track of all vehicles which currently are on its area, see attributes time-threshold, speed threshold, and jam- threshold. Further, it is possible to couple the E2 detector with a traffic light in the simulation model [9]. The output values have much information that can use to analyze the efficiencies of the traffic simulation model, for instance, averaged time loss, longest jam, jam lengths, etc. Based on different method and real data, each research should extract the crucial factors dealing with current issues in the real circumstances. In this study, there are two vital factors will drop into this essay including a jam lengths factor and a mean time loss factor.



(a) (b)

Fig. 7. The traffic simulation model of Chaoma- Chaogui intersection: (a) Lane- area Detector (E2) installed in traffic simulation model, (b) Each lane has been numbered

E2 seems to be a flexible and strong tool in Sumo software. This part is not only providing a method to capture vehicle as vehicle tracking camera, measuring the queue length in each lane in isolated intersection but also detecting the jam length in the traffic network so that researchers, decision makers can easily realize and mark the traffic jam and solve the traffic congestion on-site. In a single intersection, E2 captures jam lengths as same as queue lengths in each lane. Therefore, comparison queue lengths, mean time loss between the original traffic simulation model from the existing traffic signal and proposed traffic signal simulation based on new values of effective green time, the consequences will be convinced.

In this study, the traffic simulation model of Chaoma- Chaogui intersection has been built by Sumo software that composed two necessary information which was a network topology and a traffic pattern demand. Particularly, the network topology has been created by Net Edit tool in Sumo and then the traffic pattern demand has been inputted in the simulation model from VD data of Chaoma- Chaogui intersection. Following this, each lane in this intersection has numbered to control and get the detail information (Fig. 7) as well as E2 installed in lane 1 (lane 1_0, lane 1_1), lane 3 (lane 3_0, lane 3_1), lane 5 (lane 5_0, lane 5_1) to capture the jam length and mean time loss in each lane (Fig. 7). The simulation model has run in an hour from the 27900th second to 3600th second to simulate the traffic situation in rush hour from 7.45 am to 8.45 am in Chaoma- Chaogui intersection.

D. *Applying E2 for the Traffic Simulation Model of Chaoma- Chaogui Intersection*

The flow chart (Fig. 8) showed how the existing traffic signal at Chaoma- Chaogui intersection was optimized. It was clear that there was two mains part simultaneously in this process. On the one hand, the existing traffic signal time was simulated by open resource software named Sumo in order to build the initial traffic signal simulation model of this intersection. On the other hand, the optimum values of effective green time were minimized by the minimizing queue length method (2.1). As a result of optimal effective green time, the adjusted simulation model was built by Sumo. At the same time, E2 detectors were deployed in each lane which has been numbered (Fig 7b) to measure all movements of vehicles in each lane in both simulation models.

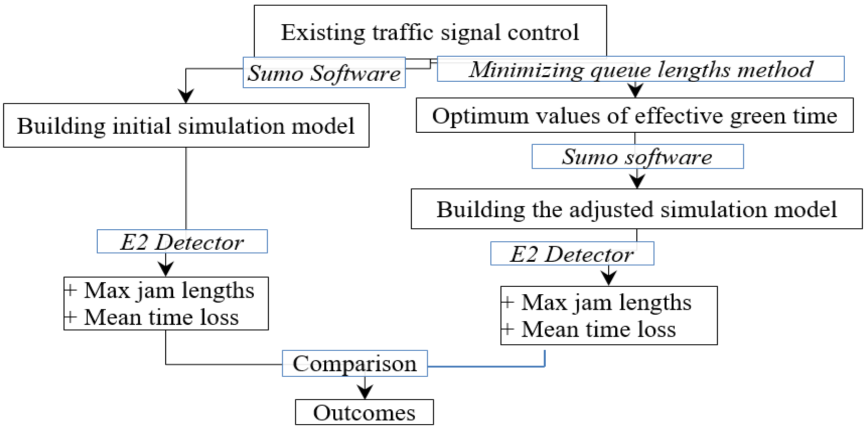


Fig. 8. Lane- area Detector (E2) installed in traffic simulation model of Chaoma- Chaogui intersection

Due to E2 data, two vital factors which were a max jam lengths factor and a mean time loss factor were extracted. Ultimately, the max jam lengths and the mean time loss were compared to convince the consequences of this method.

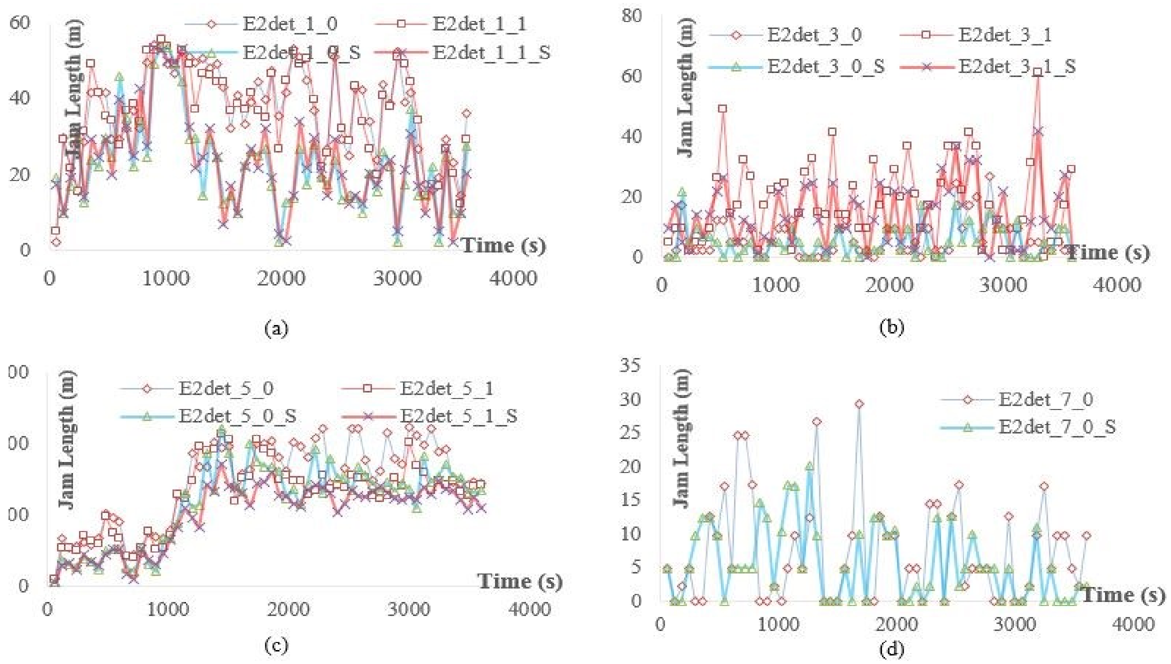


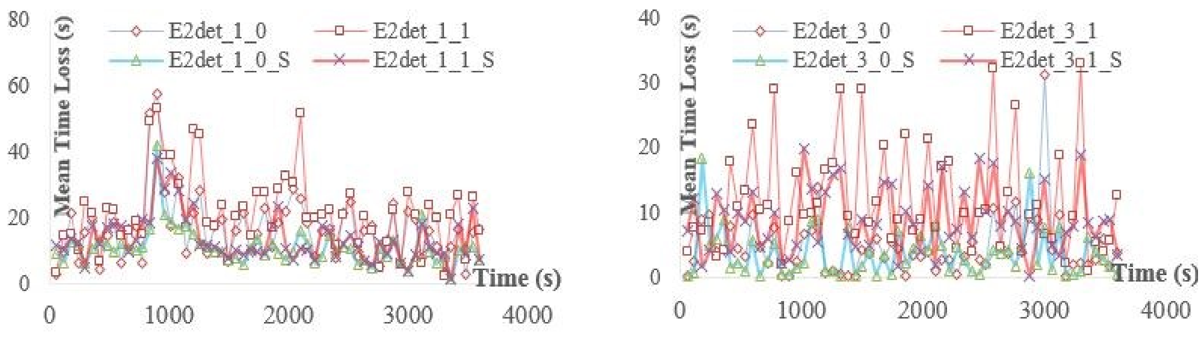
Fig. 9. The jam lengths in traffic simuation model of Chaoma- Chaogui intersection: (a) Lane 1, (b) Lane 3, (c) Lane 5, (d) Lane 7

As discussed above, the traffic simulation model of Chaoma- Chaogui intersection has simulated the traffic situation in rush hour from 7.45 to 8.45 (as same as from 27900th second to 3600th second in the simulation model). Meanwhile, the E2 output was able to describe the jam length and the mean time loss. In order to make outcomes more clearly the frequency of E2 equals 60 seconds will be generated to capture a value of the jam length as well as a value of the mean time loss for each lane. Besides, the total time to capture data is in an hour (3600 seconds), X-axis (Fig. 9).

The line charts above show how the jam length of each lane change in an hour (3600 seconds) for two traffic signal simulation models including the existing traffic signal and the suggested traffic signal. Looking at the line chart, it is immediately obvious that there are two types of line to illustrate the value of the jam length in the traffic simulation model. In particular, the normal lines describe changes of the existing traffic signal, for example, E2det_1_0 and E2det_1_1 simulate the values of the jam length in lane 1 that captured by E2det (lane area detector). Meanwhile, the bold lines that include E2det_1_0_S and E2det_1_1_S illustrate the value of the jam length in lane 1 that captured by E2 in the traffic simulation model of suggested traffic signal (_S stands for "Suggested"). The other lanes have the same manner of simulation included lane 3, lane 5, and lane 7. As mentioned in the previous section, the Chaoma road has two lanes in the Eastbound and the Westbound while the Chaogui road has two lanes in the Southbound and 1 lane in the Northbound of Chaoma Chaogui intersection. Therefore, lane 1 has lane 1_0 and lane 1_1, lane 3 has lane 3_0 and lane 3_1, lane 5 has lane 5_0 and lane 5_1, lane 7 has lane 7_0.

There are wild fluctuations in all line charts. However, it is obvious to see that overall the bold lines are lower than the normal lines. It means that the jam lengths or queue lengths of the suggested traffic signal are less than the jam lengths of the existing traffic signal in all lanes. This result demonstrates that the value of the suggested traffic signal model is more suitable and more optimal than the existing traffic signal, especially for lane 3 and lane 7, the max jam length of lane 3 is 41.48 meters in the suggested signal instead of 61.33 meters in the existing model in 3300th seconds in traffic simulation model. Simultaneously, the value of max jam length in lane 7 is 20.13 meters in the suggested model instead of 29.4 in the existing model in the 1680th second of the simulation model.

Nonetheless, there are some unexpected results that happen in lane 1 and lane 5. Particularly, the max jam length of lane 1 equals 55.47 meters in the existing model, and 53.48 in the suggested model (recorded at 960th second in traffic simulation model). The max jam length of lane 5 is 222.87 meters in existing model and 221.98 meters in the suggested model (recorded at 3000th second in traffic simulation model). Hence, there are just small changes and negligible the values of max jam lengths at lane 1 and lane 5.



(a)

(b)

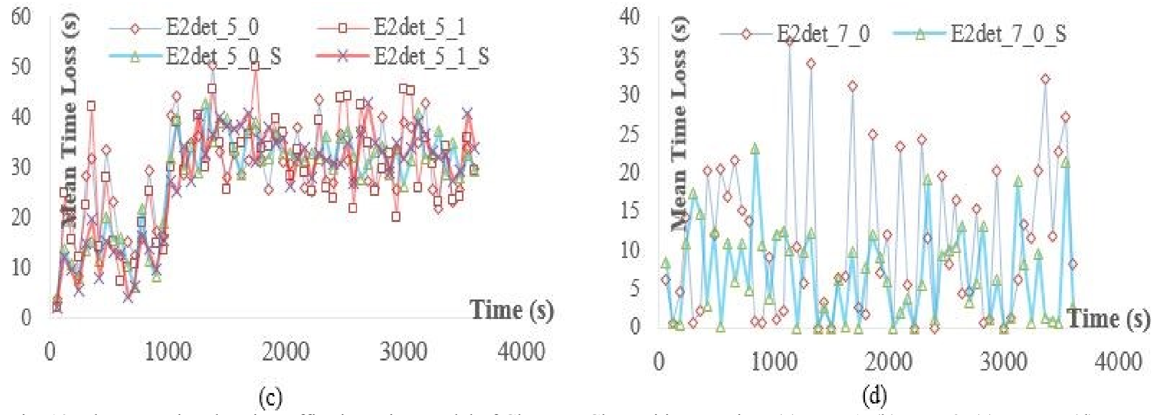


Fig. 10. The mean time loss in traffic simuation model of Chaoma- Chaogui intersection: (a) Lane 1, (b) Lane 3, (c) Lane 5, (d) Lane 7

In order to describe the value of the mean time loss for every vehicle in each lane, the same illustration manner is dropped in the graph above. Taking a look at the line graph, the normal lines (for example, E2det_1_0 and E2det_1_1) illustrate the value of the mean time loss of the existing traffic signal while the bold lines (for example, E2_1_0_S and E2det_1_1_S) are describing the value of the mean time loss of the suggested traffic signal model at Chaoma- Chaogui intersection.

As a theory, there is a positive correlation between the value of jam length and mean time loss. Looking at Fig. 10 above, it is obvious to see that bold lines are lower than the normal line to demonstrate the value of the mean time loss in the suggested traffic signal model also less than the value of the mean time loss in the existing traffic signal model. The bold lines seem to be stable and less fluctuation than the normal lines.

Especially, the suggested model is really effective in lane 3 and lane 7 when there are lots of mean time loss equal "0". Even though all lines in both models experience oscillations however the values of mean time loss in the suggested traffic model fluctuate between 0 second and 40 seconds while the values of mean time loss in the existing traffic model fluctuate from 10 seconds to 60 seconds in traffic simulation models. As discussed above, the correlation between the value of jam length and mean time loss is a positive correlation that leads to the result of lane 5 (Fig. 10). Precisely, from 1000th seconds to 4000th seconds in the traffic simulation model, the value of the mean time loss around 35 seconds in the suggested and existing traffic signal simulation model.

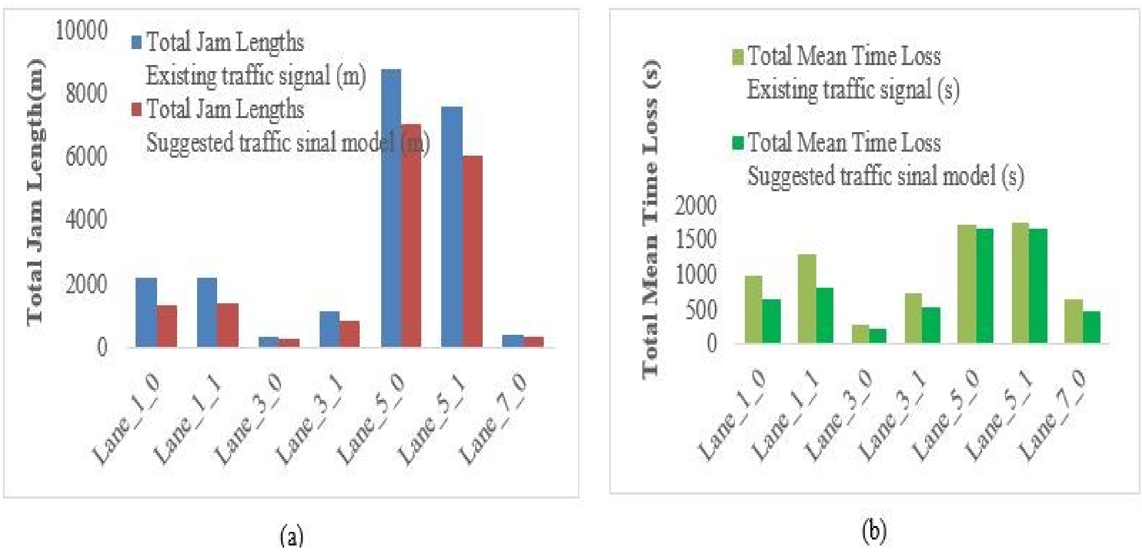


Fig. 11. (a) Total jam lengths, (b) Total mean time loss in each lane

Besides describing the value of the jam lengths and the mean time loss in each lane in real time, other vital factors need to concern are the total value of the jam lengths and the total value of the mean time loss of vehicles. Looking Fig. 9, it is clear that the relatively higher arrival rates on the through lanes lead to higher jam length and mean time loss, Lane 5 is an example. However, the suggested traffic signal control based on adjusted effective green time is more optimal than the existing traffic signal control. The total jam lengths in suggested traffic signal decrease from 58 meters to 1744 meters while the total mean time loss reduce from 58 seconds to 496 seconds have convinced the effects of the new model.

III. Concluding Remarks

This paper presented the optimal traffic signal timing for a particular intersection in Taichung city, Taiwan in a rush hour using minimizing queuing method based on Linear programming associated with Lane area detector (E2) in Sumo software. To be more precise, the linear programming that minimized the value of effective green time is more flexible than the origin theory [1] when the proposed model didn't use the fixed values of limit queue lengths in each movement in constraints referred to queue length (a and b values). It means that the different road network can use that model base on the real data, real geometry to find the optimal timing for every intersection. The results of the suggested traffic signal timing for Chaoma- Chaogui intersection convince that the proposed cycle length is 28 seconds shorter than the existing cycle length. Moreover, the output data of the E2 detector that including the value of jam lengths, the value of mean time loss demonstrated the correctness of this method. The analysis might not be the best solution to minimize queue lengths or find the optimal value of effective green time, cycle length because of some unsatisfied values are still apparent, for instance, the queue lengths and mean time loss values of Lane 5 are still high. And the limit of the linear model discussed above. However, this method opens a new solution to deal with the optimal issue in traffic control systems. Additionally, traffic and transportation are concepts with substantial financial, environmental, and social implications on the daily activities of a city [8]. Thus, the traffic simulation model in some open resources software could demonstrate and check the quality of every new methodology instead of checking in reality when changing the existing traffic signal timing that can affect to the real traffic system and wasting budgets. It might notice that the analysis using the proposed methodology will be continued and will apply for a greater number of intersections to pick up a better solution in the optimization of transport issues and further for smart mobility.

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