Algorithm for Estimating Queue Lengths and Stop Delays at Signalized Intersections

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Queue length is a basic element of urban traffic control for advanced analysis or applications. An algorithm for estimating queue lengths and stop delays at signalized intersections has been developed. The algorithm can be used to predict the queue length and the number of queuing vehicles on each approach or block to reflect actual traffic conditions by every second or other assigned time interval depending on the requirement of each traffic control center. A simulation program based on this algorithm is developed to calculate these values by considering the status of real-time traffic lights, the number of queuing vehicles left, and the location of a designated vehicle detector. Field and video measurements were made at four lanes of three intersections in Taiwan to test the predictions of this time-dependent queuing model. The preliminary results of comparisons between observed and estimated queue lengths and stop delays are encouraging and interesting. This simulation program has been installed at five TRUSTS (Traffic Responsive and Uniform Surveillance Timing Systems) in Taiwan for controlling urban traffic effectively.

When the lights are red, queues build up as a result of turning movement into the arterial at the previous intersection before the appearance of green. These values include not only turning vehicles from the previous intersection but also the vehicles that do not pass through the arterial at the end of the last green time. The phenomena are quite obvious and should not be neglected at any signalized intersection during the entire day. Queue length on each approach or block is a basic and important element of urban traffic control for advanced analysis and applications. For example, the most important variable for solving the maximum progression bandwidth is to calculate the time needed to clear the average number of vehicles standing in the queue on each block under the analysis period, such as a 15-min or 1-hr traffic flow. In other words, the incoming through-band vehicles cannot cross the intersection unless all queues in front have cleared. Therefore, it is necessary to obtain a more accurate queue length estimation to reflect traffic conditions. Through these values, the operator understands the degree of traffic congestion on each block and evaluates the suitability of current signal timing plan. The values can be further applied to find the actual shortest or second shortest routes between any origin and destination, detect the incident, or develop the adaptive control strategy.

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A new type of urban on-line traffic control system, TRUSTS (Traffic Responsive and Uniform Surveillance Timing System), has been successfully developed in Taiwan. The system involves several personal computers (PCs) that are connected by a NOVELL network. Each PC can be replaced immediately, without system breakdown, if it malfunctions or becomes functionally obsolete. It offers the user the choice of on-line timing plan generation, on-line timing table selection, or a time-of-day timing plan (*1*).

The TRUSTS wall map depicts city streets and administrative boundaries. Information on the wall map is provided by the wall map PC. The wall map capability includes displays of multiple-phase green, degree of congestion, flashing intersections, malfunctioning intersections, locations of detectors, and the 10 most congested approaches. It has several 5-cm-square polycarbonate boxes. Each box has nine lights showing the real-time traffic lights for each intersection with eight lights, including leading and lagging phases, and one-way streets. One flashing light in the center of the box represents the malfunction. The wall map PC can calculate queue length to show the degree of congestion for each approach or block. It is displayed in four colors for three indicators: occupancy, speed, and queue length. This display provides useful information to the user, and helps the user to select a suitable control strategy to cope with the current traffic condition. The relationship between the display colors and the three indicators used in TRUSTS are shown in Table 1. The occupancy and speed can be directly obtained from vehicle detectors. Queue length, however, has to be estimated from a formula or simulation program. The value used in Table 1 may vary from city to city. The large TRUSTS wall map, with its dynamic display of traffic lights and flow conditions at various threshold levels and its status display, fulfills area-wide needs. This type of wall map is very different from those used in other countries.

The PC graphic shows the real-time traffic signal system data on a color monitor. The monitor displays information on traffic lights, volume, speed, occupancy, and shortest routes. This information helps the user to understand the actual traffic conditions of a designated area or intersection. The graphics can be designed to focus on small areas, displaying increasing levels of detailed information. The monitor shows the shortest routes between two intersections, with or without considering the queue length on each approach. In addition, the graphics can provide up-to-date road and traffic information, such as the train schedule, the location and causes of a closed road,

TABLE 1 RELATIONSHIP BETWEEN DISPLAY COLORS AND THREE INDICATORS IN WALL MAP

Color	Occupancy(%)	Speed(km/hr)	Queue Length(m)
No display	≤ 10	≥ 40	≤ 20
Green	11-20	39-30	21-50
Yellow	21-30	29-15	51-100
Red	> 30	< 15	> 100

and traffic jams. The PC graphics give the user in-vehicle information through a combination of sensors and a communication system with the traffic control centers. This part, called the Advanced Driver Information System (ADIS), has been defined as one of four major intelligent vehicle-highway system (IVHS) areas in the United States.

This paper develops an algorithm for estimating queue lengths and stop delays at signalized intersections. Several variables related to this queuing model are discussed. In order to perform the sensitivity analysis and practical applications, a simulation program based on the algorithm considering the current signal timing plan is also developed. The output prints estimated queue lengths and the number of queuing vehicles by lane at the end of each 15-sec counting interval. Field and video measurements of queue lengths and stop delays test the accuracy of the predictions of this time-dependent queuing model. Field observations are made at four lanes of three intersections for a number of counting intervals at each site.

PREVIOUS FORMULAS FOR ESTIMATING QUEUE LENGTHS AND DELAYS

Catling (*2*) developed formulas to estimate mean queue lengths and delays under both undersaturated and oversaturated conditions for an interval with a stationary mean arrival rate and starting with zero queuing length. Later, he extended the work to cover variable demand levels and non-zero initial lengths. Branston (*3*) investigated the formulas for observations in three traffic peaks at sites in London and concluded that reasonable results could be obtained. The estimated mean queue length is valid only at discrete intervals of time, namely, the beginning of successive red periods. Mean queue lengths at other times during a cycle must be calculated from these values with a knowledge of the arrival rate and saturation flow. Shawaly et al. (*4*) concluded that the arrival flow delays have a significant effect on the resulting queuing length and delays even though the departure pattern remains unchanged. Kimber and Daly (*5*) found that queue length and delay predictions are particularly difficult when demand reaches capacity. Steady-state approximation no longer holds, and time-dependent stochastic methods must use approximation to cope with what is in reality a complex time development of the queuing states involving difficult sampling problems. The observed data indicated a big variation about the estimated mean profile of queues and delay.

TRANSYT is one of the most popular computer programs for optimizing the signal timings of a network with coordinated intersections. Because TRANSYT simulates traffic for a single cycle, the calculated queue length represents only that which would occur because of traffic arriving during that cycle (*6*). Queues do not build over time. The queuing model assumes that all vehicles travel the full length of the link before joining a stationary queue, thus forming vertical queues at the stop line. Although this model is not realistic, it deals adequately with the delay imposed on traffic at intersections. That is, TRANSYT does not consider queues spatially, nor does it limit the length of queue at any stage relative to the length of the link. The total number of departures using the saturation flow rate equals the number of vehicles in the vertical queue, including the vehicles joining after the start of green. The TRANSYT queue model is shown in Figure 1. This type of estimated queue length at the stop line usually gives rise to an overestimate of queue length. The estimation becomes more serious with the increase in queue length (*7*).

TIME-DEPENDENT QUEUING MODEL

The arrival pattern of the algorithm is established so that the traffic joins the back of the queue with the consideration of actual vehicle lengths. It can avoid an overqueuing situation due to the block-length constraint. After the beginning of green, a vehicle in the queue remains stationary until it is reached by the start wave. Before the queue is cleared, vehicles in the queue discharge at a speed associated with the saturation flow. The queue length will be continually added up from the incoming traffic until the start wave reaches the back of the waiting queue. At this moment, the queue length immediately becomes zero. Although conceptually it may not be reasonable that the queue length becomes zero after the last vehicle in the queue is reached by the start wave, in field tests the queue length estimation on each approach or block still represents the actual value in most cases. After the total queue disappears, vehicles move off at the same speed as the arriving traffic before the traffic light turns to yellow and all-red. It is hoped that queues can be cleared from the most distant detectors during green phases. If traffic flow increases still further, queue lengths may extend beyond the most remote detectors and the computation of the queue length will be terminated or need more assumptions.

The queue length defined here is the number of vehicles from the stop line of a signalized intersection to the back of the last stationary vehicle in the queue, irrespective of whether vehicles other than the last vehicle are moving. Queuing vehicles, however, represent the number of vehicles that are actually stopped in order to estimate the stop delay. These two major items, queue lengths and queuing vehicles, are considered separately in this time-dependent queuing model.

The dynamics of this time-dependent queuing model are shown in Figure 2. The queue length in this figure increases from one to two units of vehicle length at the end of 5 sec

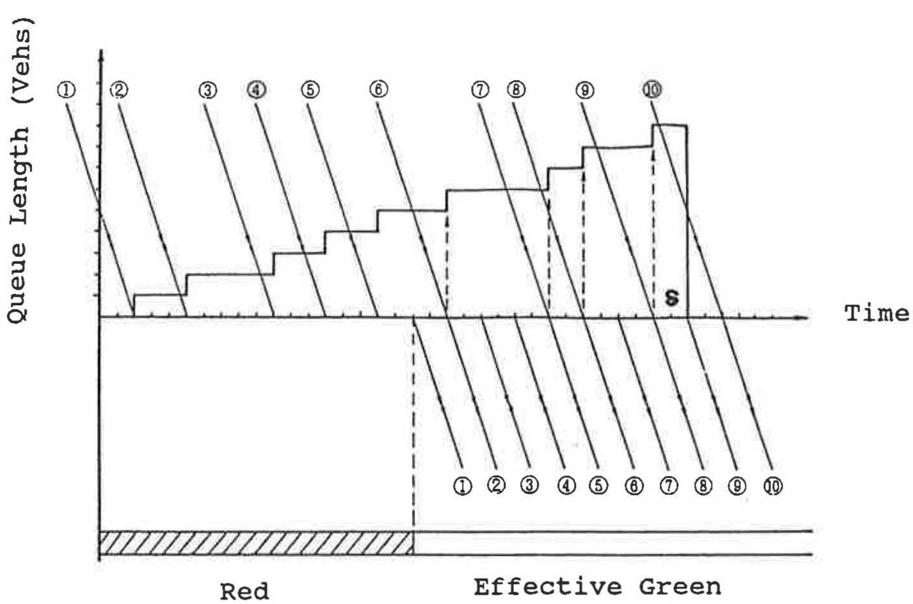

FIGURE 1 Queuing model for TRANSYT.

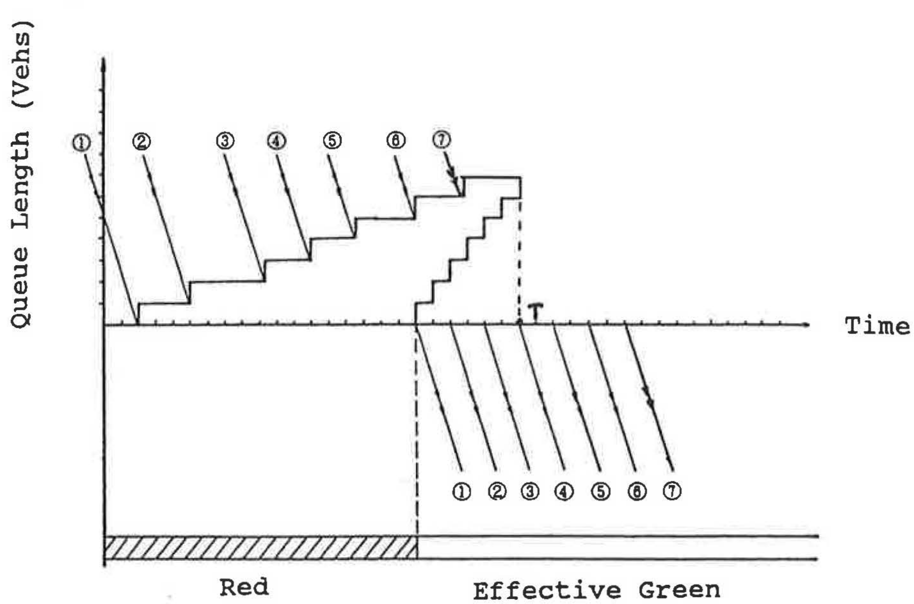

FIGURE 2 Dynamics of time-dependent queuing model.

(one step equals 1 sec) after the beginning of the red. Then the queue length becomes three units at the end of 9 sec and so on, until it reaches the maximum length of six units at 18 sec in this example. As the light turns green, the queue length still increases to seven units, and this last stationary vehicle is reached by the start wave at 24 sec (symbol *T* in the figure). The estimated queue length defines zero after that time. In the meantime, the seven vehicles in the queue dissipate with a saturation flow rate of 2 sec per vehicle and clear at the end of 30 sec.

In a real situation, the number of vehicles queuing varies continually from cycle to cycle. This time-dependent queuing model provides a measure of the estimated queue length and queuing vehicles at the end of every second or a longer defined interval. It not only shows the number of vehicles stationary in the queue but also indicates the actual waiting distances. At a signalized intersection, traffic delays usually result in queues. Vehicles in such a queue are likely to remain stationary and can be used to calculate stop delays through the number of queuing vehicles instead of the estimated queue length. Therefore, the actual stop delay for each queuing vehicle is simply determined by subtracting the stop time after its arrival from the next moving time. These stop delays are then summed up over each time period and averaged for the total number of vehicles that arrived during the same time interval. The delay equation in the 1985 *Highway Capacity Manual* (HCM) (*8*) was developed from both uniform delay and random delay through deterministic queuing models. With real-time traffic inputs, the average queue size cannot be estimated through this delay equation second by second or for a 15-sec time interval. Therefore, the 1985 HCM delay equation considers the number of queuing vehicles and stop delay through the macroscopic concept accompanying a complete cycle length. The proposed time-dependent queuing model, however, considers the microscopic movement in an assigned short period.

Queue length represents the result of a complex function of vehicle moving speed, length and type of arriving vehicles, location of vehicle detector, start wave speed, geometric shape, and lane-change behavior. Some variables are discussed here. Vehicles, after passing the vehicle detector, usually maintain a constant speed for a few seconds, then decelerate gradually to stop and join the last queue vehicle. This is a nonlinear procedure and is difficult to trace accurately because there are not enough detectors to provide the needed information along each block. One simple way to solve this problem may be to use a lower constant speed. The variable for length and type of each incoming vehicle can be directly estimated from the vehicle detector and classifier. It is easy to use this value in the time-dependent model through the TRUSTS equipment. The variation in the start wave speed during the effective green stage has a varying degree of importance, depending on the number of vehicles queuing. If a higher start wave speed is assumed, then the time needed to clear the estimated queue length will be decreased, and vice versa. A better way to obtain this value may be observing the videotape of field tests based on different locations of vehicle detectors. For the lane-change behavior, the model becomes very complex if each vehicle is traced, and advanced electronic equipment is required to record the movement of all vehicles. Therefore, for simplicity, the lane-change variable is not considered at this stage.

In order to obtain the estimated queue lengths and stop delays from the real-time traffic lights, a simulation program, written in C language, was based on the above concept. The flow chart of this program is shown in Figure 3. The program first checks the status of the signal timing plan. If the light is red, the program continues to calculate the accumulated queuing vehicles and stop delays by every second or other assigned time interval. After the light turns green, the program automatically investigates the queue length whether or not it has been cleared. If the answer is negative, the program not only accumulates the number of vehicles in the queue but also traces the reaching location of start wave in order to estimate queue length, queuing vehicles, and stop delay. If the answer is positive, the queue length remains zero until the next red phase. The program continues to compute the queue length and the number of queuing vehicles at the end of each assigned time interval and prints the time of queue length cleared.

This program allows the user to perform sensitivity analyses by setting different values of variables. The input items include the average approaching speed, distance from the detector to stop line, current signal timing plan, and time of each vehicle passing through the detector. Figure 4 shows the portion output of estimated queue lengths and queuing vehicles for a 15-sec interval and average stop delay throughout test periods. This example assumes that the average vehicle length has a magnitude of 6 m with no lane-change behavior. The start wave occurs in the beginning of the green phase

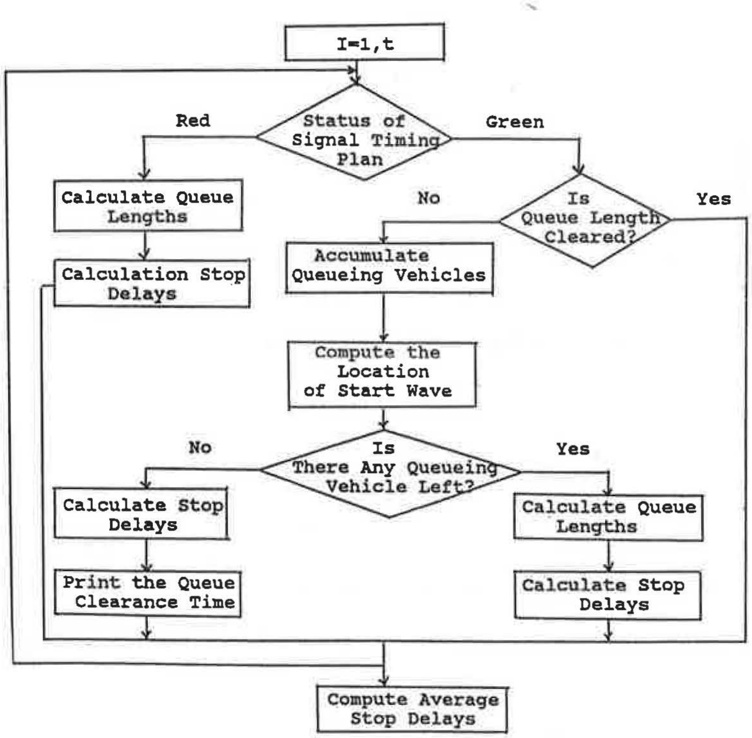

FIGURE 3 Flow chart of simulation program based on time-dependent queuing model.

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        Estimated    The Location     Queueing
Time      Queue        of Start       Vehicles
         Lengths         Wave
**************************************************
35:00      0      -      0      =      0
35:15      0      -      0      =      0
35:30      0      -      0      =      0
35:45      4      -      0      =      4
36:00      9      -      0      =      9
36:15     14      -      0      =     14
36:30     15      -      9      =      6

Queue lengths were cleared at 36:36

36:45      0      -      0      =      0
37:00      0      -      0      =      0
37:15      0      -      0      =      0
37:30      0      -      0      =      0
37:45      2      -      0      =      2
38:00      8      -      0      =      8
38:15     10      -      0      =     10
38:30     12      -      9      =      3

Queue lengths were cleared at 38:33

  .        .      .      .      .      .
  .        .      .      .      .      .
  .        .      .      .      .      .
  .        .      .      .      .      .

48:45      0      -      0      =      0
49:00      0      -      0      =      0
49:15      0      -      0      =      0
49:30      0      -      0      =      0
49:45      6      -      0      =      6
50:00     12      -      0      =     12
50:15     15      -      0      =     15
50:30     17      -      9      =      8

Queue lengths were cleared at 50:38

50:45      0      -      0      =      0

Total vehicles:  192

Average stop delay per vehicle:   18.97 sec/veh
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FIGURE 4 Portion output of estimated queue lengths, queuing vehicles, and average stop delays.

with a speed of 1.1 veh/sec based on various observations of videotapes. The assumed values of these variables may vary from city to city.

COMPARISONS OF OBSERVED AND ESTIMATED VALUES

Queue length estimated by the proposed comprehensive time-dependent queuing model is compared with queue lengths actually observed during six different time periods. To obtain more accurate and reliable field data, the minimum time of observation was 15 min for each counting period. Measurements were made at four lanes in three intersections in Taichung City, Taiwan. Lanes A and B were located in the same approach; Lanes C and D, however, represented two different approaches. The selected lanes allowed manual and video measurements of the physical length of road occupied by the queue. The field measurement included the observed queue length and stop delay at the end of a 15-sec interval during total counting periods. The developed simulation program and videotapes allow the user to calculate and investigate the queue length second by second or for a longer time interval depending on the requirement of a local traffic control center. The observed stop delays were obtained through a point sample procedure that was found to be the most practical method for measuring the intersection delay in the field. A video system with two cameras collected the required data. The first camera focused on the vehicles passing through the vehicle detector, and the second camera recorded the entire process of vehicle movements from the upstream to downstream intersections with a time sequence on the screen. The two video cameras and observers' watches were synchronized to a common time base before the start of observations.

The preliminary comparisons of observed and estimated queue lengths by lane during six counting periods are shown in Table 2. This table includes the mean queue length and its standard deviation, the distance from the vehicle detector to stop line, the sample size of each counting period, and the percentage of accurate estimation for four different lanes at various periods. Some discrepancies were found between observed and estimated results. From this table, the estimated values from Lanes A and B were more accurate than those obtained from Lanes C and D by over 20 percent. This discrepancy was probably due to the fact that the travel distance to stop line for Lane D was 100 m longer than for Lane B after vehicles passed through the vehicle detector. This finding implies that vehicles may overtake one another and distort the sequence of recorded queue vehicles during the arriving process from the location of existing vehicle detector to the last queue vehicle. Therefore, the estimated results are sensitive to this value, which is a strongly site-dependent parameter.

The relationship between estimated and observed values during test periods for Lanes B and D are shown in Figures

TABLE 2 COMPARISONS OF OBSERVED AND ESTIMATED QUEUE LENGTHS FOR FOUR LANES

Lanes	Counting periods	Distance from Detector to Stop-Line (Meters)	Estimated Queue Length (Vehs)	Estimated Queue Length Standard Deviation (Vehs)	Observed Queue Length (Vehs)	Observed Queue Length Standard Deviation (Vehs)	Total Sample	Same Sample	Percent (%)
A	1	65	0.32	0.69	0.49	0.98	96	80	83.3%
	2	65	0.67	1.11	0.81	1.18	135	105	77.8%
B	1	65	0.60	1.07	0.70	1.26	96	75	78.1%
	2	65	0.96	1.40	0.83	1.15	135	99	73.3%
C	3	100	2.60	3.11	2.47	2.86	176	92	52.3%
	4	100	1.10	1.48	1.34	1.49	62	32	51.6%
D	5	165	3.70	4.66	3.38	4.48	64	38	50.4%
	6	165	4.76	5.84	3.09	5.10	80	40	55.1%

5 and 6. The irregular trend of actual queue length during test periods is shown. Comparisons of estimated and observed values by considering one vehicle difference are shown in Table 3. This table shows that at least 70 percent of estimation from the simulation program is reasonable. That is, the estimated queue lengths can represent actual values in most cases for a 15-sec interval.

Table 4 shows the differences between observed and estimated stop delays. The estimated stop delays are directly obtained from queuing vehicles instead of the estimated queue length. The observed stop delays are collected through the point sample method. The raw value for stopped time is multiplied by 0.92 to represent the observed stop delay. This multiplier factor applied to the raw field data achieves a better estimate of the true value. The coefficient 0.92 was recommended by Homburger and Kell (*9*) and can be varied from different locations if sufficient field data are available. The differences shown in Table 4 range from 3 to 28 percent. From these values, it can be concluded that the estimated stop delay, as well as the queue length calculated through this proposed time-dependent queuing model, apparently represents the actual value.

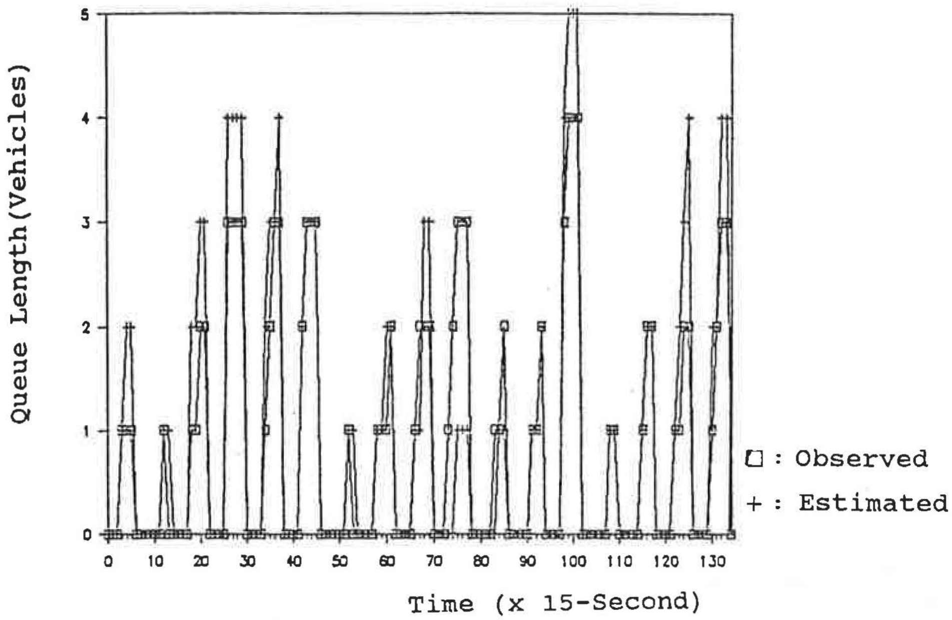

FIGURE 5 Relationship between estimated and observed values during test periods for Lane B.

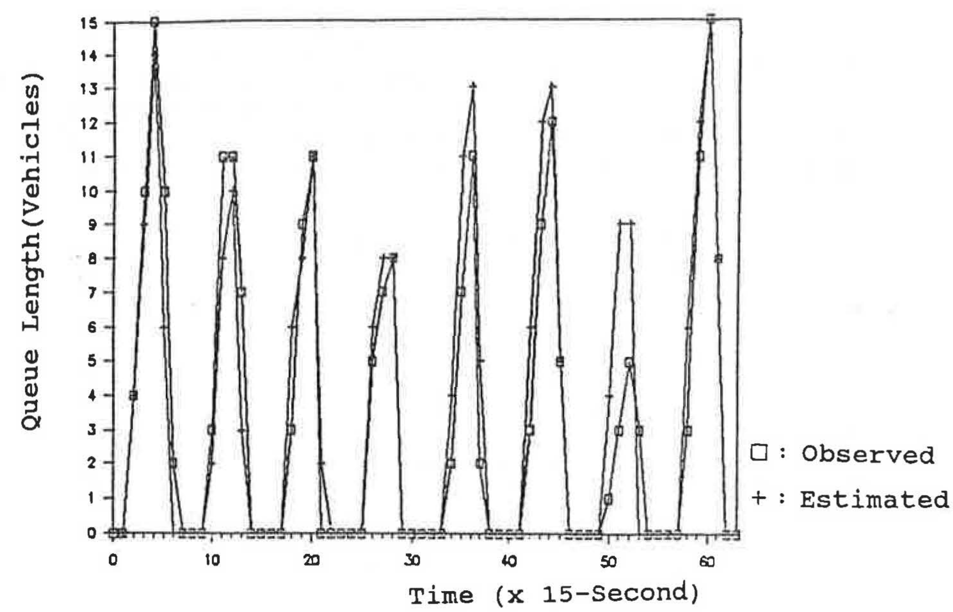

FIGURE 6 Relationship between estimated and observed values during test periods for Lane D.

TABLE 3 COMPARISONS OF ESTIMATED AND OBSERVED QUEUE LENGTHS CONSIDERING ONE-VEHICLE DIFFERENCE

Lanes	Counting Periods	Less One Vehicle (%)	Same (%)	One Vehicle More (%)	Total (%)
A	1	14	83	1	98
	2	15	78	5	98
B	1	8	78	5	91
	2	3	73	20	96
C	3	13	52	12	77
	4	19	52	8	79
D	5	8	59	6	73
	6	9	55	6	70

TABLE 4 COMPARISONS OF ESTIMATED AND OBSERVED AVERAGE STOP DELAYS FOR FOUR LANES WITH DIFFERENT COUNTING PERIODS

Lanes	Counting Periods	Estimated (sec/veh)	observed (sec/veh)	Differences (%)
A	1	2.46	3.08	-13.6%
	2	4.54	5.25	-13.5%
B	1	3.89	4.02	- 3.2%
	2	6.07	4.74	28.1%
C	3	22.51	28.19	-20.1%
	4	10.72	13.84	-22.5%
D	5	18.97	16.96	11.9%
	6	20.49	19.82	3.4%

CONCLUSIONS

An algorithm for estimating queue lengths and stop delays at signalized intersections has been developed. Based on the information of incoming traffic and the current signal timing plan, the algorithm can be used to predict queue lengths and the number of queuing vehicles for every second or other time interval assigned according to the needs of a traffic control center. Preliminary comparisons of observed and estimated queue lengths and stop delays are encouraging. The proposed time-dependent queuing model considers several related variables but some are simplified in the process of estimation. More research on certain variables, such as lane-change logic and approaching speed, is needed.

Queue length on each approach or block is a basic element of urban traffic control for advanced analysis or applications. This information is used in the wall map and computer graphics of TRUSTS to represent the degree of congestion for various blocks. Through this estimated queue length, TRUSTS can provide in-vehicle information to drivers, such as the actual shortest route or second shortest route between any origin and destination. The next step for this study is to add the estimated queue length into the performance index function of each approach in order to develop a new type of adaptive control that is different from the concept used in OPAC (*10*) or SCOOT (*11*). Some interesting results have been obtained and will be presented later.

Finally, a simulation program based on this algorithm has been installed at five TRUSTS in Taiwan. The display of degree of congestion on different blocks shows the operator the actual traffic conditions of the entire area. It allows the user to quickly spot the problem through the large wall map and computer graphics. The operator can change the signal timing plan or immediately alert the patrolling police to the congested areas from the control center. So far, TRUSTS controls urban traffic flow effectively in Taiwan.

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