Adaptive Predictive Traffic Timer Control Algorithm

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ABSTRACT

In this paper, we study the optimization of traffic light controllers and present an adaptive, predictive, and statistical optimization algorithm that performs dynamic queue length estimation. The system presented focuses on low power consumption, easy maintenance, and simple construction. The highlights of the system are (1) dynamic queue length estimation for timer delay computation and (2) the signal coordination algorithm it employs. Adaptive logic focuses on estimating the queue length during run time using sensors. The sensors need not be activated if a pattern is observed in the traffic flow. This forms the substratum for the predictive logic. Statistical data is used when the queue length exceeds a threshold. The green time for each traffic signal can be varied between a pre-estimated minimum and maximum, depending on the traffic flow. The red time for a particular signal depends on the green time of its complementary signal. The queue length detectors that we propose to use are fundamentally sensor networks that are composed of through-beam photoelectric sensors, arranged in an efficient topology. The efficiency of the algorithm has been estimated by conceptually applying the algorithm to a busy intersection in Chennai, India. The related statistical comparison with current systems has been presented. The algorithms have been simulated using a computer program written for the Turbo C++ compiler. An optimized signal coordination algorithm is presented that utilizes an online timing update technique for efficient traffic flow.

Key words: adaptive control—online timing update—signal plan optimization

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INTRODUCTION

A common function of a traffic control system is to minimize the delay experienced by vehicles traveling through a road intersection by manipulating the signal plans. The primary categories of a traffic control system are pre-timed and adaptive systems. Under pre-timed operation, the master traffic signal controller sets the signal parameters based on predetermined rates. These values are determined from historical data collected by observing the traffic flow. Common practice for developing pre-timed signal plans utilizes offline tools such as TRANSYT, which are based on traffic flows and queues observed from field data (McShane 1997). Pre-timed control frequently results in the inefficient usage of intersection capacity because of the inability to adjust to variations in traffic flow and actual traffic demand; this inefficiency is pronounced when flows are substantially below capacity. An adaptive controller overcomes the problem of a pre-timed controller by operating signals based on traffic demands. The green time for each approach can be varied between a minimum and maximum, depending on flows. The main feature of an adaptive controller is the ability to adjust the signal phase lengths in response to traffic flow.

Various efficient systems have been proposed. The most notable of these are SCOOT (Hunt 1982), developed in England, and SCATS (Lowrie 1982), developed in Australia. Both SCOOT and SCATS are adaptive-cyclic systems, in that they update the signal time plan at pre-specified time intervals. Other known methods under development over the last decade include PROLYN (Henry 1989), UTOPIA (Mauro 1990), OPAC (Gartner 1990), etc. These systems attempt to optimize traffic on-line without being confined to a cyclic time interval; i.e., the signal time plan may change at any time depending on the optimization algorithm. Compared to pre-timed signal control, these systems undeniably improve overall performance in terms of total delay in the controlled network. The usual improvements amount to roughly 10% (Boillot 1992).

This paper introduces an adaptive predictive signal control system that performs real time queue length estimation and employs an efficient signal coordination algorithm. The signal coordination algorithm proposed plans to optimize traffic at run time without being confined to a cyclic time interval. The real time queue length estimation is done by an array of simple through-beam photoelectric sensors placed in an efficient topology. Here the signal plan changes during each cycle based on inputs from the timer delay estimation algorithm. Though no new mechanism for detecting pedestrians has been proposed, the signal coordination algorithm takes care of pedestrian crossings as well. The timer values for pedestrians are based on historical data. The next section gives a detailed description of the proposed system architecture.

APTTCA SYSTEM ARCHITECTURE

This section presents the overall architecture of the proposed APTTCA-based system. The system consists of the following six components: (1) sensor network, (2) green time estimation module, (3) database, (4) signal plan design, (5) signal controller, and (6) traffic signal lights and timers. Figure 1 presents the architecture of the proposed system and the relationships between the various components. The bold lines indicate actual flow of control in the system. The dashed lines imply exclusive data flow.

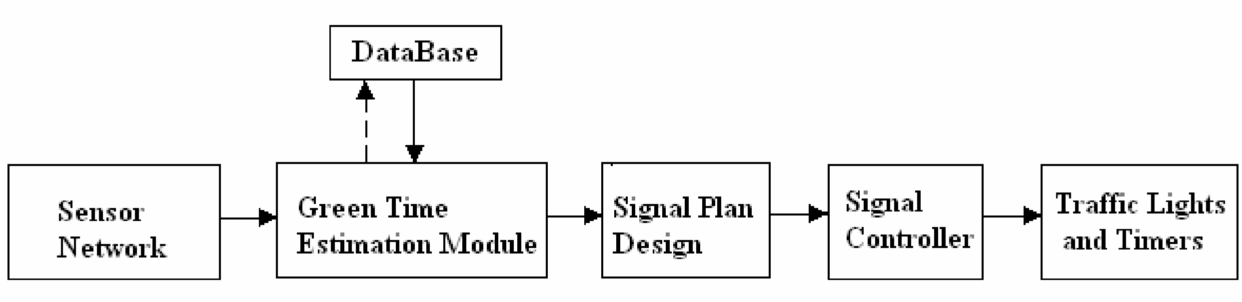

Figure 1. APTTCA system architecture

The core of the proposed system uses the queue lengths determined by the sensor network. The adaptive signal control logic attempts to respond directly to run time traffic variations. The green times are allotted based on the queue length estimated. The signal plan design module works on these values to provide an efficient traffic plan that ensures low average intersection delays and avoids starvation. The signal controller finally generates the necessary control signal for the output devices.

REAL TIME QUEUE LENGTH ESTIMATION: THE APTTC ALGORITHM

The heart of the system is its queue length estimation algorithm. The algorithm works by imposing an initial condition that when the signal is switched “on,” all the lights (i.e. the traffic lights in the various directions) are red. The queue length detector is switched “on” in each direction. The queue length detectors are primarily arrays of photoelectric sensors. The number of sensors in the queue length detector array varies in each direction. The size of the sensor array (i.e. the number of sensors for a particular direction) is estimated by observing the nature of traffic in the intersection under consideration at all times of the day, distributed over a week.

All the sensors of the array are not activated at one time; they are turned “on” only when they are needed. This forms the basis of the power-efficient adaptive queue length estimation procedure. The procedure is explained below.

Adaptive Queue Length Estimation Algorithm

Initially, only the first and the last sensor pairs are activated. The reason behind the use of sensor pair outputs is that even if one sensor fails to detect a vehicle because the vehicle has stopped just before or just after a sensor, the other in the pair will surely respond. This is possible because the distance between two sensors has been designed suitably. The output of a pair is high if either of the sensors in the pair detects a vehicle. It is low if both the sensors of a pair fail to detect a vehicle. When the first and the last sensor pair outputs are examined, four cases arise.

The first case follows: if both do not detect a vehicle, then the green time is set to a minimum value, usually zero. After a small time interval, ‘t_{ic}’ or “inter-computation time,” the process is repeated.

The second case is the other extreme: both sensor pairs detect vehicles. In this case the Green time is set to a maximum value calculated from statistical data.

The third case is when the first sensor pair detects a vehicle and the last does not. This situation clearly indicates that the queue is not completely full. Here the algorithm takes a binary search-like approach. Assuming ‘2n’ to be the number of sensors in the array, the $(n/2)^{nd}$ sensor pair is activated and its output taken. If it is high (i.e., it detects a vehicle), then the upper half becomes the area of interest with the $(n/2)^{nd}$ pair assuming the role of the first pair. Now the $(3n/4)^{th}$ sensor pair is switched "on" and the process continues until the first and the last sensor pair under consideration becomes the same. This is the length of the queue. This is used to calculate the green time.

The fourth case, namely the first pair not detecting a vehicle while the last pair detects a vehicle, is assumed to be impossible. This is because we consider sensor pair outputs, which at least theoretically do not commit such errors.

Predictive Logic

To begin, the algorithm is completely adaptive. This goes on for the first week of operation. The queue length estimated in real time over this period is stored in a database. This database now has information about the traffic flow at all times of the day, over a week. This data is sufficient to predict signal timer values in the near future.

After the first week of operation, say, on a Monday morning, the values obtained at, say, seven hours is compared with the value for Monday at seven hours in the database. If it matches, the values for the very next cycle of the signal are taken from the database and the sensors are not turned "on." The tolerance allowed is given by $t_{obs}=t_{db} \pm d$, where t_{obs} is the timer value observed at the moment, t_{db} is the database entry for the same day and time but in the preceding week, and d is the allowed deviation fixed at 10% of t_{obs}. If the above equality is not observed, t_{db} is replaced by t_{obs}. This implies a change, usually an increase in the number of vehicles passing the intersection. Hence this algorithm vouches for a significant change in traffic conditions.

Hence, the word "predictive" in the APTTCA context does not imply the conventional "predictive" commonly used in other traffic algorithms. Here we predict the timer values of the near future in the same intersection. This approach avoids the overhead due to unnecessary sensor activation and timer delay computation. This improves the efficiency of the system, reduces component wear and tear, and increases the life of the system.

Use of Statistical Data

Adaptive queue length estimation has been in consideration only because the pre-timed control systems, those using historical data, become inefficient when the flow of traffic is much less than the intersection capacity. Hence, suitably collected data obviously becomes the best choice when the queue lengths estimated are at their maximum. This data is stored in a database, which is subject to constant updating. The system is constantly observing the flow of traffic in the intersection. This information is used to update the statistical data stored in the database. Hence, a near-accurate timer delay estimation becomes feasible. If a traffic signal is constantly experiencing maximum queue lengths, it is an indication that the size of the sensor array has to be increased, since intersection usage has increased.

HARDWARE FOR REAL TIME QUEUE LENGTH ESTIMATION

The system proposed uses simple, well known, and inexpensive hardware for queue length estimation. This section is composed of subsections that deal with the technical specifications of the sensors, the topology in which they need to be arranged for effective queue length estimation, the optimal height at which they need to be placed, the optimal spacing between the sensors, and finally a comparison with the existing vehicle identification system.

Technical Specification of the Sensors

The most commonly used sensors are loop detectors, or photo sensors. The heart of our research is photo sensors. There are basically three types of photo sensors: through-beam, retro-reflective, and diffuse-reflective. The range at which the sensors need to operate is 50–100 ft. The only type that satisfies this requirement is the through-beam. Many manufacturers promise similar features. Table 1 shows a fraction of a datasheet provided by the Warner electric company.

Table 1. Sensor specification

Sensing principle	Sensing range	Input voltage	Output mode	Max cycle range	Output current	Model
Through Beam	500 ft	10 to 30 V DC	NPN	>25Hz	250 mA	MCS-629
Through Beam	50 ft	12 to 18 V DC	NPN	>250Hz	250 mA	MCS-627

Sensor Network Topology

A single photoelectric sensor cannot do the job. An array of sensors placed suitably is needed. The sensors should not interfere with pedestrians. Hence, they are placed in the intersection of the road and the pavement. We need to detect the vehicles waiting in each lane of the road. The transmitter of the first sensor is placed in the intersection of the road and the pavement, and its receiver is placed on the road, right on the lane separator line. The casing of this receiver has enough space for the transmitter of the sensor for the next lane. The receiver for this transmitter is placed on the subsequent lane separator. The final receiver (i.e., the receiver of the last lane detection array) is placed on the median. Figure 2 illustrates the sensor network topology for a four-lane intersection. Note from the figure that the number of sensors in each direction is not the same. It has been fixed based on the anticipated traffic flow and is subject to change.

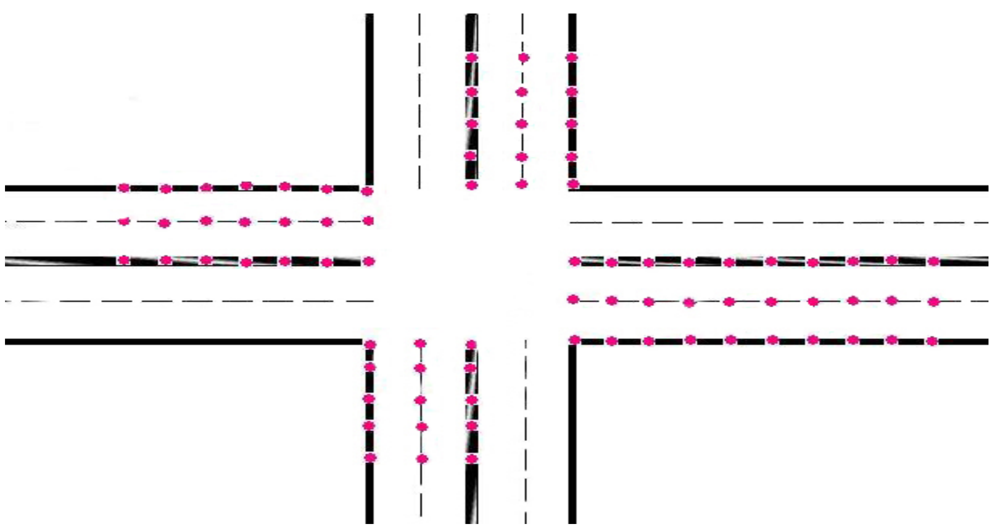

Figure 2. Sensor network topology for a four-lane intersection

Optimal Height of Placement

The sensors have to be placed at a comfortable height so that they can detect any vehicle. This has been estimated by conducting a study on various categories of commercial vehicles. The ground clearance information has been used to fix the optimal height. The highest ground clearance is found to be 18.5 inches for a dump truck. Providing a 0.5-inch tolerance, the height is identified as 19 inches. The study was conducted among 12 categories and 57 models of vehicles from 14 manufacturers around the world.

Sensor Spacing

The sensors have to be spaced so that they can effectively detect vehicles. They are also used to determine the length of the queue waiting at the signal. This information is multiplied by a suitable factor to obtain the green time for that direction. The spacing should not be so large that small vehicles that have placed themselves between the sensor pairs go undetected, nor should they be so small that more sensors will be needed for a small section of the road. This can be fixed based on a survey on various categories of vehicles in common use. The total length of the vehicle has been used as a parameter in determining the distance between the sensors. The length varies from 181 inches to 464 inches. A large number of vehicles have lengths lying between 220-230 inches. Thus, we can approximate the distance between the sensors to 240 inches. This distance has been verified manually and has an efficiency of over 65%.

Advantages

The proposed system promises a few non-performance–related advantages over current systems. Current systems generally use inductive loop detectors.

Robustness

The major advantage of an APTTCA-based system is the robustness and the ease of maintenance it offers. The queue length estimation system is not going to fail because of a single sensor malfunctioning. The job will be done by its partner. This is not the case with inductive loop detectors, whose failure leads to failure of the system. Thus an APTTCA-based system is more robust than existing vehicle detection systems.

Ease of maintenance

Another advantage of the proposed system is the ease of maintenance it offers. Inductive loop detectors are placed beneath the road, making it difficult to repair or replace the malfunctioning component. In this system, the sensors are placed 19 inches above the ground in a plastic casing, and hence replacing and repairing them is easy.

SIGNAL COORDINATION IN APTTCA

Adhering to the golden rule of traffic control, the signal coordination algorithm used in APTTCA gives priority to long queues. The inputs to the signal coordination module are the estimated timer delay values. The APTTC algorithm is applied to all directions possible at the intersection. Timer values for each direction are obtained from the estimated queue length. The queue length is added to the length of the intersection and the timer value is fixed as the time taken by a vehicle traveling at 15 kph to cover this distance. The timer values for the pedestrian crossings are obtained from historical data based on the time of the day. This means that the pedestrian delay value is picked up from the database based on the time and day of the week. The value for a pedestrian crossing on a Sunday afternoon will not be equal to that on a Monday morning.

The main aim of the coordination algorithm is to generate a signal plan that ensures efficient flow of traffic. This performs an online signal update, which means that the system is not cyclic and that no road user can predict what is going to happen next. This system is not completely dynamic. This means that if a direction has been allowed for, say, 60 seconds, it will not be considered until all other directions including the pedestrians have been given a chance. Completely dynamic systems may lead to starvation.

The Algorithm

The algorithm begins by obtaining all the green times for each direction of the signal. These are the demands of traffic. An algorithm is needed to meet this demand effectively. Each direction is associated with a green time. The input is an array of green times. The algorithm sorts this array in the descending order. Three arrays are maintained. They are the waiting array, the running array, and the completed array. The waiting array consists of the directions that are currently red, sorted in descending order. The running array is made up of those directions that are currently green. The completed array consists of those directions that have completed their turn. The timer display is turned off for those in the completed array.

Initially, the waiting array is full and the other two arrays are empty. The largest (i.e., the first) element of the array is the candidate that is made green, and the timer count is set to the estimated value. This entry is removed from the waiting array and is entered into the running array. The subsequent direction in the waiting array is taken. This is compared for compatibility with the entries in the running array; if it is not compatible, the red time for the chosen candidate is made equal to the green time of the contradicting entry. If there are no compatibility issues, then the chosen candidate is removed from the waiting array and appended to the running array. The entries in the running array are removed once their green time becomes zero. Their signal value is made red and the timer is turned off. This is repeated until the waiting array has no candidates. This ensures that there is no starvation. The pedestrians are also considered as a direction in this algorithm. Figure 3 depicts a six-lane–six-lane intersection with the various possible directions. The algorithm for the intersection shown will initially have 16 entries in its waiting array: 12 entries for vehicles and 4 for pedestrians. The diagram does not show the sensors.

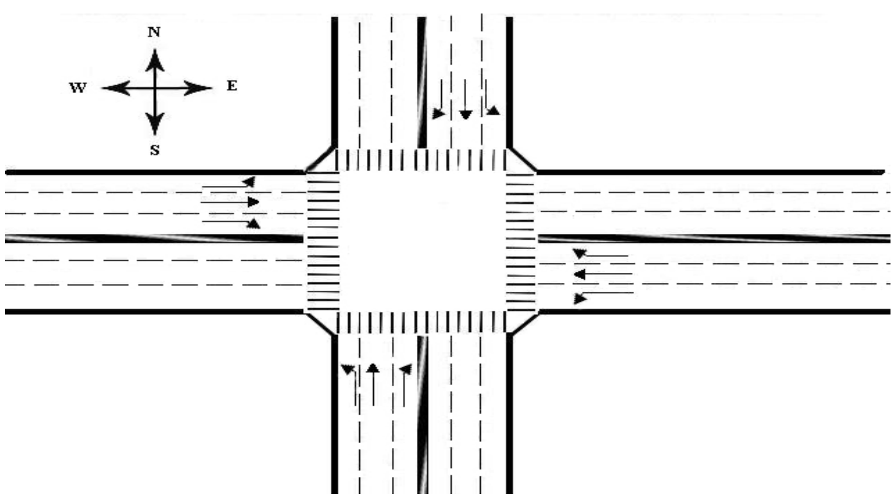

Figure 3. Six-lane–six-lane intersection

RESULTS

The algorithm has been theoretically implemented at the Mount Road-Venkatnarayana Road intersection in the city of Chennai, India. The sensors were not actually installed at the intersection, but queue lengths were determined manually at various times of the day for two full weeks. This queue length data is being used as the basis for the results derived. The algorithms were simulated using C++ programs. Table 2 shows the average values of the input data collected at the test site. This data has been used as input for the signal plan simulation program. The values shown were collected during various times of the day for two full weeks.

Table 2. Data collected at the test site

Day	Time of measurement (peak/off-peak)	Avg. queue length (meters)*	Avg. pre-timed timer value (seconds)	Avg. pre-timed timer based on time of day (seconds)	Avg. timer value APTTCA-based (seconds)
Monday	Off-peak	34.4	55	20	11.5
Monday	Peak	154.5	55	55	54
Wednesday	Off-peak	30.2	55	20	10.5
Wednesday	Peak	150.5	55	55	51
Friday	Off-peak	31	55	20	10.5
Friday	Peak	148.5	55	55	50
Sunday	N.A	64.5	55	45	24.5

* Manually estimated

The most important observation to be made is the amount of time wasted during weekends and off-peak periods using pre-timed control. Though pre-timed control that differentiates between peak and off-peak periods overcomes this, it can never be accurate as APTTCA-based systems. Thus, the results clearly indicate that APTTCA is efficient no matter the day or time. Figure 4 graphically depicts the variation in traffic flow.

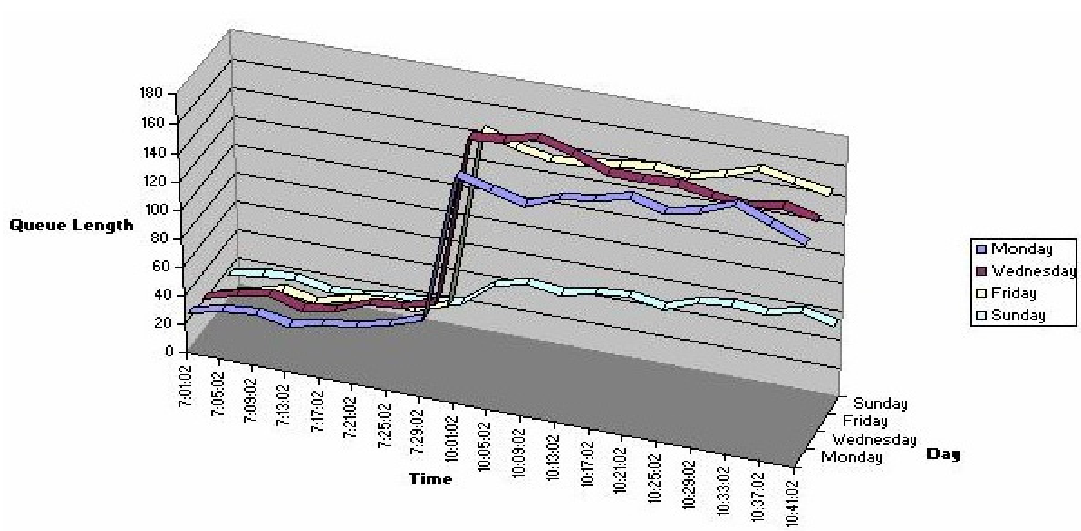

Figure 4. Variations in traffic flow

The signal plan simulation program considers the following: 1) pre-timed control, 2) pre-timed with time of day, and 3) APTTCA-based control. This program generates a signal plan and calculates parameters such as signal delay and throughput. The signal plan generation is based on the algorithm explained in the previous sections. The results are tabulated in Table 3.

Table 3. Performance results

Traffic system	Throughput per cycle (no. of vehicles)*	Average delay (sec/vehicle)	Performance improvement based on avg. delay %
Pre-timed control	235	45.5	N.A
Pre-timed control based on time of day	221	40	12.22
APTTCA-based control	218	37.5	17.58

* Includes pedestrians

The results show that the proposed system clearly outperforms the older systems. Though the throughput values are better for a pre-timed control system, the real measure of performance is the average delay. The APTTCA-based system clearly promises less waiting time. The results shown are average values from five simulation runs.

RECOMMENDATIONS

The next advancement to the system proposed is regarding pedestrians. An efficient technology that detects the number of pedestrians waiting to cross the road should be developed. This can be done using systems such as video recorders or even photoelectric sensors. The system was developed for a single intersection. A natural extension would be to address intersection coordination. Now that we have developed an efficient traffic control system, we must work to control the genesis efficiently (i.e., provide efficient control over the drivers of various vehicles). In order to do this, an efficient navigation system should be developed and communicated efficiently. A scheme compatible with APTTCA should also be developed. Another type of improvement is to use more dynamic signal coordination algorithms. These can surely improve the efficiency of the system.

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