The Area-Wide Real-Time Traffic Control System (ARTC): A Distributed Computing System

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Abstract

This paper presents a distributed computing system, Area-Wide Real-time Traffic Control (ARTC) 1, designed to provide areawide smooth traffic progress and to prevent frequent occurrences of traffic congestion. The signal controllers in ARTC, which are microcomputers, are interconnected through a computer network. By exchanging traffic flow information among the signal controllers, ARTC provides a new concept in areawide traffic control by exploiting the use of the computer network. Simulation results of the ARTC prototype control algorithm is presented, and the results show substantial improvement over an optimized fixed time control. The signal controllers and the computer network are designed to support the real-time communication requirements and a sufficient level of fault-tolerance.

Index Terms — Computer applications, real-time traffic control, traffic congestion, fault-tolerance, computer networks

1 Introduction

The growth of the number of vehicles on the roads has put a higher demand on the traffic control system to efficiently reduce the level of congestion occurrences, which increases travel delay, wastes fuel, and increases air pollution. Traffic congestion may occur due to exceptional traffic conditions such as peak-hour traffic, accidents, road-side friction, traffic fluctuations, etc.

One of the prevalent problems is that most of the current traffic systems are unable to control transient congestion, since they may not be sensitive to traffic fluctuations. Though the use of computers in real-time traffic control has been put into practice by various systems like SCOOT, SCAT and OPAC, the effectiveness of the computer network and spatially distributed signal controllers has not been fully exploited [1, 2, 3].

One reason is that a major number of the current traffic control systems do not have effective areawide control for a traffic network consisting of freeways, arterials and cross streets. There are two basic requirements which need to be met when providing real-time traffic control: acquisition of traffic flow information and analysis of this information to provide optimal control. The above tasks have to be performed in a reasonably short real-time interval, for the traffic control has to be highly responsive. Advanced concepts for traffic control using network wide information about traffic flow has been pointed out by Haver and Tarnoff [4]. The current computer controlled signal systems can be classified into two categories: fixed time control which uses signal plans computed off-line using past data, and traffic-responsive control which computes the signal plans according to the prevailing traffic flow [5, 6, 7, 8, 9, 10, 11]. Most of the current traffic control systems such as SCOOT, SCAT and ATSAC, which are computer controlled, fall under the traffic-responsive category [1, 2, 3, 12, 13, 14].

The traffic network under SCOOT and SCAT is controlled by a single computer which serves as a centralized controller. The signal controllers, which are less powerful computers connected to a centralized controller through leased telephone lines, perform simple tasks such as collecting the traffic flow information, sending it to the centralized controller and implementing the signal phase plans. Further more the traffic network is divided into regions and each region is controlled by a regional controller. The inter-regional traffic flow information is exchanged by the regional controllers which is used to regulate inter-regional traffic. In these systems, the signal controllers heavily depend on the regional controller to compute the signal plans, hence when the regional controller fails, all the signal controllers in the region fall back to the primitive control strategy of using fixed time plans. Since most of the signal timing computations are performed by the regional controller there is a significant overhead, and the communication network may be congested due to enormous influx of messages from the signal controllers.

In this paper, we present an efficient software ap-
The concept of ARTC's signal timing computation and control is that the signal controllers in ARTC interact with each other to compute the signal timing plans such that no road can be congested and the average delay time for vehicles is minimum. The signal controllers measure the average flows in each road entering the intersection, known as an approach, and accordingly decide if a synchronized offset should be provided for any particular signal and phase. The regional controller observes the global view of the traffic network and appropriately sends congestion control and progression commands, which are explained in this section.

3.1 Signal controller computation

The signal controllers use traffic control strategies which are executed depending upon the flow rates measured at the entry detectors and the flow at the neighboring intersections. The signal timing decisions made by the signal controller at an intersection are also sent to its neighbors, which if possible will provide a progression to the dense group of moving vehicles, called a platoon. Moreover a synchronization of the signal timing plans is utilized when a steady and heavy flow in one direction is detected by consecutive controllers, which determine the path of the heavy flow. A common cycle and split length for these controllers is computed by one of the controllers in the path which acts as the master controller for the synchronization.

3.1.1 Progression and congestion control

Each signal controller after beginning a split, will send a message to the signal controllers in its neighboring intersections to which the platoons will travel to. The main elements in the on-line control strategy in the ARTC system is the estimation of the queue, the computation of the split length and progression request propagation [15]. The basic philosophies adhered to in ARTC are the following:

1. A vehicle stops at most once, at an intersection
2. A vehicle queue must be discharged in the split
3. Appending vehicles during queue discharge must also be dissolved in the same split.
3.2 Regional controller algorithm

At a higher level of control, the regional controller periodically checks the flow pattern changes in the traffic network and detects any traffic path which shows a rapid increase in flow. The detected path is then checked to see if it is safe to provide a progression and if so, a progression factor, which indicates the offset timings, is provided to the signal controllers in that path. If the above detected path shows signs of creating congestion then a congestion control factor, which is a restriction of the green length for the traffic flowing along that path, is provided to the signal controllers.

The split computation for each phase change is performed just before the actual change of each phase as explained in the steps below.

1. At scheduled change for phase, compute the flow rates for both directions, i.e. $f_{red}$ and $f_{green}$, which represent the flow rates at the approach with the red phase and green phase respectively.

2. Find the split duration of the current green phase $t_{green}$ and the duration of the past red phase $t_{red}$

3. Compute the Delay per car, $D_{green}$ and $D_{red}$, in the approaches currently at the green phase and red phase respectively.

4. Extend the current green phase as long as the total delay $D_{green} + D_{red}$ is minimum and go to step 1.

When there is a heavy flow in both directions of a stretch of road, then it is very difficult to give a progression to both the traffic flows. However, it is reasonable to give a progression to one direction of the traffic if it is extremely higher than the other. If the traffic flows in both the directions, for example east and west, are comparably high, then we provide a partial progression for both the flows, which we call the $M:N$ progression. That is, the total number of intersections is $(M + N)$ along the path of heavy flow, which is in both directions of the road. Then a ratio of the flows will provide an indication as to which flow gets a progression of up to $M$ intersections with synchronized offsets.

To enforce congestion control it is sufficient for the signal controllers to limit the inflow of vehicles into the approach leading to the neighboring intersection. Before each phase change, the signal controller in each intersection gathers the load values of the approaches leading into its neighboring intersections. If a particular approach carries a load higher than a predefined threshold value, then it limits the influx of vehicles into that approach by turning the signal lights for that approach to red. Once the affected approach dissipates its load, the neighboring signal controller will resume normal operation and send vehicles into the approach.

3.2.1 Traffic flow information

A signal controller maintains the traffic flow information for incoming approaches and this information is periodically updated and collected at the regional controller for every time period $\Delta t$. To indicate degree of traffic flow of an approach during a time period $\Delta t$, we use a parameter which is the ratio of the vehicles in the approach to the maximum volume of traffic that the approach can carry, which we call the Vehicle-to-Volume Ratio (VVR) of that approach.

The VVR data is used to identify the heavy flow approaches by defining a range of VVR to be a critical zone, which implies that the traffic in an approach is dangerously high if its VVR value is in the critical zone. For safer estimation we represent each discrete range of the VVR in levels. An approach is said to be in a potentially critical state if its current VVR level is found to be higher than the critical level.

The signal controllers periodically send a the current VVR of all approaches incident on it. Each time this information is collected, the regional controller forms the traffic information graph (TIG). Each node in the TIG represents a controller of an intersection. The directed edge between two nodes represents the approach between two intersections and the level of flow of the corresponding approach is associated with each edge, as shown in Figure 2.

If the level of flow in an edge is in the critical zone, then the edge is called a critical edge. A path formed by the critical edges is called a critical path. When a critical path is detected in the TIG, the regional controller computes the duration of the green phase for the controllers in that path to reduce the flow along the path. In this way, the traffic flowing into the path is gradually reduced experiencing a moderately longer delay but avoiding imminent congestion.

One of the major functions of the regional controller is to provide traffic flow information to the central control center. With our approach, we believe that the information can be effectively collected, displayed, and used for various purposes.
3.2.2 Detection of critical paths

The regional controller uses a list structure to represent the TIG. Each edge with an unique identifier represented in the data structure used for the computation is as follows:

| Edge ID | Source | M | Destination | P₁ | P₂ |

where P₁ denotes a set of pointers to outgoing critical edges from the destination, P₂: set of pointers to incoming critical edges from the source and M: number of incoming critical edges to the source. To detect the critical paths, the regional controller performs the following steps:

1. All non-critical edges are removed.
2. Select a critical edge.
   - Mark this edge as $H_{edge}$.
   - If no such edge is found, goto step 4.
   - (2.1) Visit the node incident on the tail.
   - (2.2) Select a critical edge incident on the node.
   - (2.3) Repeat (2.1) and (2.2) until a node with no critical incoming edge is visited.
   - (2.4) Visit node incident on the head of $H_{edge}$.
   - (Now, the search continues in a reverse direction beginning at $H_{edge}$.)
   - (2.5) Select one critical edge incident on the node.
   - If no such edge is found, goto step 3.
   - (2.6) Repeat (2.4) and (2.5) until a node with no critical outgoing edge is visited.
   - (2.7) Store the node visited at the last step in the above process as the head of the path.
   - (As an edge is visited, it is stored in a linked list, and then it is removed from the TIG.)
   - (The operational complexity of the above steps is $O(E)$, where $E$ is the number of edges in TIG. Now, each linked list represents a critical path.)
4. Visit the node with more than one incoming critical edge, $N_{1}$, and find the path that has $N_{1}$ as its head.
   - Merge the two lists.
5. Search the lists for critical paths to find a node at a tail of a path whose identifier matches $N_{1}$.
6. Repeat 4 and 5 until all critical paths are visited.

The computation described thus far takes $O(P)$ operations, where $P$ is the number of critical paths in the graph. The detection of path with outstanding but not yet critical traffic level can be done in a similar manner.

3.3 Exceptional conditions

During exceptional conditions like accidents, variable traffic flows, and failure of signal controllers, the performance of the traffic control system may be reduced. Hence, these exceptional conditions have to be detected and dealt with appropriately to provide better control.

The consequence of accidents is usually a reduction of flow rate in the affected approach, such that the flow rate downstream to the accident is low compared to the flow upstream of the accident. At the signal controller, the incoming and outgoing flows can be measured from the entry and exit detectors respectively and a difference in flows can be detected and used to detect blockages in the road. The detection of variable traffic is done by comparing the immediate past traffic levels of the approach with the current traffic level. These variable traffic flows which might impede any outstanding paths are identified by the regional controller and a priority for progression is given to the outstanding paths, thus providing them with uninterrupted flow. In cases where two outstanding paths cross each other, the regional controller computes the split and offsets along the paths for ensuring smoother flow.

The failure of a signal controller is informed to the neighboring signal controllers of the failed controller by the regional controllers and these signal controllers restrict their flow into the affected intersection. Since the failed controller will not be able to provide its neighboring controllers with the flow rate and load information needed for their signal split computation, the regional controller provides this data which is estimated by using the history traffic flow data of the failed controller.

4 Performance

A simulation of the ARTC was performed and compared with the results of an optimized fixed time signal control plan. The timing computation for this fixed time control was done off-line with the use of the TRANSYT7F program for the specified arrival rates and geometry of the intersection. This program is based on a macroscopic model of the traffic network and the optimized signal plans are designed offline, with the average flows, for a traffic network [16].

The model which we simulated consisted of a 2 x 2 grid with four intersections, as shown in Figure 3. Three lanes were provided for each approach, with the left lane being exclusively used for vehicles making left turns and the right lane being shared by vehicles turning right and straight ahead. The center lane was used by vehicles moving straight ahead only. All vehicles were programmed to travel at a uniform fixed speed and were allowed to change lanes. Entry detectors were placed at the entry point of each lane and exit detectors were placed at the exit point of each lane, which are shown in Figure 3. The arrival rates of the vehicles, which is specified as an input parameter, is generated at the specified rate.

A simple two-phase sequence was used in the timing plan, and two all red periods, which were 3 seconds long, were provided between each phase. This 3 seconds of all red represented the loss time experienced by the vehicles during each phase change.

To compare the performance of the traffic control methods we identified three important performance parameters which we explain below. These output parameters can concisely describe the quality of the traffic control when compared with the performance results on other traffic systems under the same environment.
- **Average delay per vehicle:** A vehicle comes to a stop at an intersection if the signal light for its direction is red and hence waits at the intersection until it changes to green. This waiting time at the intersection is the delay experienced by the vehicle and should be minimized.

- **Mean number of stops:** This parameter can account for the average number of stops a vehicle has to experience while traveling through the road network which is under control by the traffic control system being simulated. The performance of the system is better with a lower number of stops.

- **Travel efficiency:** A vehicle can pass through the road network without pausing at any intersection or reducing its normal speed of travel, and the time taken for this ideal travel is the least one can attain. The actual time taken by all vehicles to pass through the system is measured and is divided by the total number of vehicles to give the average time taken by a vehicle to pass the system. The ratio of this average time to the ideal travel time gives us the travel efficiency of the traffic control system. The goal of the traffic control system is to achieve a higher value of travel efficiency.

Figure 4(a) and 4(b) plot the average delay per vehicle against time and the the mean number of stops against time. As can be seen from the figure, both the delay per vehicle and the number of stops per vehicle are much lower using the ARTC control strategy. This is due to the fact that the on-line strategy computes the split depending upon the instantaneous measurement of the traffic flow data. Moreover, the queue estimated by ARTC was marginally higher than the actual queue and hence in addition to dissolving the queue provided the necessary progression for the vehicles approaching the intersection.

In Figure 5 plots the travel efficiency against time, for both TRANSYT and ARTC control strategies. The travel efficiency of vehicles in ARTC indicates that the vehicles experience much less delay than when compared to vehicles in TRANSYT. Moreover, the travel efficiency is related to the average delay experience of vehicles.
rienced per vehicle, hence a lower average delay per vehicle will yield a higher value of travel efficiency.

5 Conclusion and future direction

In this paper we presented the ARTC system which provides effective congestion prevention and areawide progression. The application of computers in the field of transportation is vital as can be seen in the development of the ARTC system is still under refinement to improve its performance. The traffic network which was simulated was small and hence did not reflect the full capability of the ARTC system and has more potential to improve its performance.

One of the major advantages of employing the ARTC is that it prevents congestion rather than detecting it after it has occurred. Moreover, the progression of traffic can be achieved at a high level in the ARTC since the signal controllers are able to communicate with each other. Even though the above aspects of traffic control can be achieved to a sufficient level by the communication between signal controllers, the regional controller is provided for efficient areawide traffic control coordination. Since the regional controller has a global view of the traffic network, it provides non-linear progression and also detects anomalies such as accidents and traffic fluctuations. From the simulation results it can be seen that ARTC performs better than the fixed time control plan which was computed by TRANSYT. The delay per car and the mean number of stops have been significantly reduced by the use of ARTC’s control strategy. Currently the simulation has been performed on the traffic network and the regional controller is currently not used.

The failure of a signal controller does not affect the performance of the traffic control system in a drastic way, since the regional controller provides the necessary data for signal timing computations. But to provide better fault-tolerance, the signal controllers are designed in a modular structure with the computation module being replicated.

With minor modifications to the controllers it is possible to expand the ARTC system to accommodate the functions to be provided by the Intelligent Vehicle-Highway System (IVHS). The computation methods for the control algorithms in the ARTC system are still under refinement to improve the performance. The traffic network which was simulated was small and hence did not reflect the full capability of the ARTC system.

References


