

Time-dependent Travel Time Estimation Model for Signalized Arterial Network

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5144 Words + 6 Figures + 1 Table

Submittal for the
86th Annual Meeting of the Transportation Research Board
July 31, 2006

Abstract

Travel time estimation on arterials is a challenging task for traffic engineers due to the interrupted nature of urban traffic flows. Many research efforts have been devoted on this topic, but their successes are limited and most of them can only be used for offline purposes. One of the drawbacks common to the previous studies is the under-utilization of traffic data from existing infrastructures. With the advancement of intelligent transportation systems, high-resolution detector and signal status data are available but not fully explored. In this paper, we propose and design a data-intensive time-dependent arterial travel time estimation model by exploiting the available detectors and signal status data from the existing infrastructures. Available high-resolution data are collected and analyzed to estimate the intersection delays and the arterial travel times are generated by aggregating the intersection delays based on the time of arrival. Performance of the proposed method is tested using a microscopic traffic simulation model, which simulates a hypothetical arterial network. Preliminary results have demonstrated that the proposed model can generate accurate time-dependent travel time under various traffic conditions.

1. Introduction

Travel time is one of the most important measurements for evaluating the performance of traffic networks and accurate and reliable travel time information becomes increasingly important for traffic engineers. Also, travel time is one of the most understood measures for road users to perceive the current traffic conditions, and help them to make smart decisions on route choices, and hence avoid unnecessary travel delay. Travel time can also be used for either optimizing the operation of existing traffic infrastructures or developing new advanced traveler information systems and traffic management systems. In the last few years, measuring and monitoring performance of traffic management systems has become one of the priorities of Federal Highway Administration (FHWA) as indicated in the new transportation bill SAFETEA-LU.

The interrupted nature of traffic flows under the urban environment makes the travel time estimation much more challenging for arterials than for freeways. During the past decade, research studies on freeway travel time estimation are rich and successful; some products from these studies have been implemented on freeways. For example, the freeway Performance Measurement System (PeMS), developed by the PATH program at UC Berkeley, is one of the most notable systems that can collect and analyze real-time freeway traffic data, and generate comprehensive performance measures including travel time (1). On the contrary, research on arterial travel time estimation is limited. Though travel time has long been recognized as a valuable measure for the effectiveness of the arterial network, no comparable system like PeMS has been developed and implemented for surface streets with signalized intersections. The difficulty is that travel time on arterial networks is usually not only a function of traffic flow, link capacity and speed limit, but also involves with numerous other factors such as signal timing and conflicting traffic from cross streets.

Previous research on arterial travel time estimation generally provide an offline assessment between two points based on the distance, volume and static signal settings data. The most famous and widely used function is the so-called BPR function that proposed by the Bureau of Public Roads in 1964 for planning purpose which solely

considers the relationship between the travel time and volume/capacity ratio (2). In many previous works the travel time is calculated by separating it into two parts, one is the cruise time, and the other is the delay. The cruise time is measured as the time required for the vehicle traversing the link under prevailing traffic conditions without signal or queuing delay. The Highway Capacity Manual (HCM) incorporates the concept of control delay in its travel time estimation procedure, which is based on the vehicle arrival type, signal setting data, and queuing information (3). The Webster formula is commonly used to calculate the average signal delay near the stop line of an intersection (4). It derives from the deterministic queuing theory with the assumption of fixed signal setting. Though these approaches can describe the average network performance to certain extent, they are not suitable for dynamic traffic applications especially under congestion.

Some manual travel time data collection methods such as probe vehicle are also widely used in the practice, especially on arterials. In spite of the dynamic and stochastic attributes of the traffic network, the probe vehicles can be used to collect travel time data as a representation of prevailing traffic conditions. The Travel Time Data Collection Handbook provides a good reference on this method (5). However, the approach is labor intensive and time-consuming, and can not provide continuous travel time estimation over a long period. Similarly, some researchers try to use transit vehicles as probes for travel time estimation (6). However, the estimated measures from buses may not reflect the true travel condition of passenger cars, which is the majority of urban traffic population. This method is also site-specific and can only measure the travel times along the bus route.

Data from inductive loop detectors has been used to estimate the freeway travel time. One of the methods estimates the average travel speed (inversely proportional to link travel time) from point-based loop detector flow and occupancy data, with the assumption that space mean speed is a simple function of spot mean speed (5). However, the method is inaccurate under urban environment because the speed measured at the detector location can not represent the traffic conditions along the whole link, especially those near the intersection. The point traffic measures can hardly interpret the dynamic

factors associated with the traffic signal such as vehicle queues. Therefore, the point-based travel time methods, which solely rely on single loop detectors, can not be used for arterial travel time estimation.

Another category of arterial travel time estimation model is based on the idea of identifying a vehicle at the upstream and re-identifying the same vehicle at the downstream (7). Recent improvement on detector technologies provides vehicle signatures for the vehicle identification method. The advantage of the approach is that the complexity of the arterial networks could be ignored, while the estimation would be accurate and timely as long as the identification accuracy is guaranteed. Similar approach can be applied to the platoon re-identification (8). Video detections are also widely used to identify the vehicles with either their visual characteristics (9) or their license plates (10, 11) via video images on arterial streets. In addition, some ongoing researches are considering exploring the cellular location technology or acoustic methods to track the vehicles with mobile phones in them or identify the acoustic signature of vehicles' engines. However, the major drawback of the identification approaches is the high cost to implement these advanced systems. The effectiveness of such immature approaches on urban streets has not been sufficiently tested, and privacy issues may be involved with license or cell-phone identification.

Statistical model is another class of travel time estimation methods for arterials. Regression equations are fitted between travel time and the traffic variables of the study network, such as flow, occupancy, speed and signal timing. Linear (12), non-linear (13), and Bayesian (14) models have been proposed, and varying degree of success has been claimed by the researchers. The major drawbacks of the statistical models are site specific and have to be recalibrated to fit other environments. Artificial Neural Networks (ANNs) are also employed to develop arterial travel time models with the fusion of multiple data source, such as surveillance data, probe vehicles, and license plates (15, 16). However, most of the models are proposed and tested under simulation environment and lack of transparency. Further field research is needed to gain experience for practical travel time estimation.

While the previous research works on arterial travel time estimation achieve success to certain extent, they often have restrictions to be implemented to real world environment or are difficult to generate accurate results. The major limitation of previous models is that they do not fully utilize the available data from existing infrastructures to estimate travel time. Most of these models only take into account the information from the surveillance system, while the status of signal data are omitted or less considered. Though recent research by Skabardonis and Geroliminis (17) derives an analytical model based on data collected from both loop detectors and signal settings, their model does not examine the dynamic property of the signal timings and is complex to be implemented. The signal status data is especially important for travel time estimation model when the traffic signals are not fixed-time.

The purpose of this research is to develop an effective travel time estimation model which fully utilizes the surveillance data collected from existing loop detectors and the real-time signal status information, in a synchronized manner. We assume that the high-resolution volume/occupancy data from loop detector and signal status data are available, which has been demonstrated in previous researches such as the Traffic Signal Performance Measurement System developed by Balke, et al. (18). The field detector and signal data are transmitted via wires to a database located at the management center, and the proposed model analyzes the data and generates the time-dependent travel time by recursively aggregating the travel time and delays along the intersections of the corridor. The proposed algorithm can be applied in both stable un-congested and unstable congested traffic conditions.

The paper is organized as follows. The data collection architecture is presented in Section 2. Detailed description of the proposed arterial travel time estimation model is offered in Section 3, including the system layout and the calculation procedures of free flow travel time and intersection delay. Performance testing and analysis of the implementation with a hypothetical arterial network are followed in Section 4. Finally, the concluding remarks and future research directions are offered in Section 5.

2. Data Collection Architecture

The advancement and deployment of telecommunication and ITS technologies make real-time and historical traffic data more readily available. Generally, two types of raw data can be retrieved from the signal controller. One is the data from vehicle detection unit and the other is the signal status data. Actuated traffic controllers receive all of their information regarding the current state of the traffic system in the form of detector calls, typically from inductive loop detectors cut into the pavement surface. These calls, or actuations, simply indicate a vehicle arriving “event” happens, and the vehicle demands service for a particular movement. In addition, signal status changes can be also regarded as an “event”, and both vehicle actuation event and signal status change event can be logged. The feasibility of such “event” data collection and archiving from traffic signal system at individual intersection has been demonstrated by the Traffic Signal Performance Measurement System (TSPMS) developed by Balke, et al. (18).

Availability of high-resolution loop traffic data and signal status data provides traffic engineers opportunities to further improve the effectiveness of current closed-loop control systems. Currently, the authors are undertaking a project jointly sponsored by the Intelligent Transportation System Institute of the University of Minnesota and Minnesota Local Road Research Board to develop a traffic signal performance measurement system for arterial networks. The project is in collaboration with the Traffic Management Center (TMC) of the Hennepin County. In this project, the event data from the loop detector and signal status will be recorded and archived. Figure 1 demonstrates draft system architecture for the data collection and archiving of the arterial performance.

A database is physically located in the central computer of TMC. The database receives inputs through wire connection with super master and local signal controllers in the field. The system analyzer module calculates a set of performance indexes, which are stored in a database at the University Traffic Lab. The performance measures can be also accessed by the outsider users through the Internet. One of the performance measures derived from the raw data the point to point travel time along an urban arterial, which is the topic of this paper.

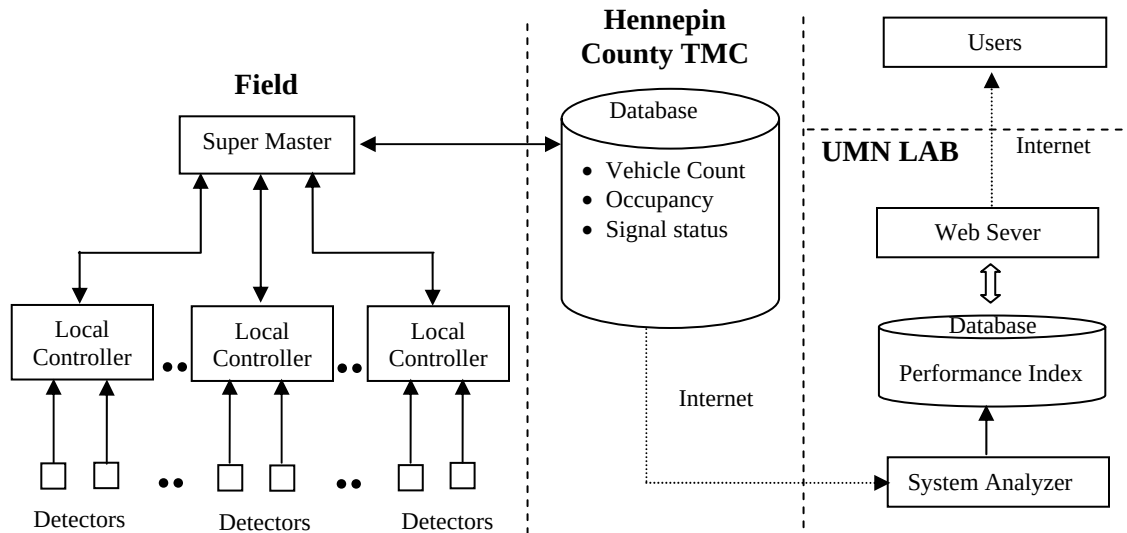


Figure 1. Draft System Architecture

3. Arterial Travel Time Estimation Model

3.1 Arterial Signal System Layout

The proposed arterial travel time estimation model utilizes both the surveillance data measured from loop detectors and the signal status data collected from traffic lights. [Figure 2](#) represents the geometric layout of an arterial network. The time-dependent travel time from the origin O to the destination D need to be estimated as indicated in the figure. There are n signalized intersections, i.e. Intersection 1, Intersection 2, till Intersection n , along the corridor from O to D . Assuming all the intersections adopt vehicle-actuated signal timing plans, in either synchronized or non-synchronized mode. Each approach of the intersections should install at least one advanced loop detector, which is indicated as $d_1, d_2 \dots d_n$ in Figure 2. For simplification, we only give the description of the corridor travel time estimation of eastbound flows, i.e. from O to D , and the corridor travel time of the flows on reverse direction can be calculated with similar procedures.

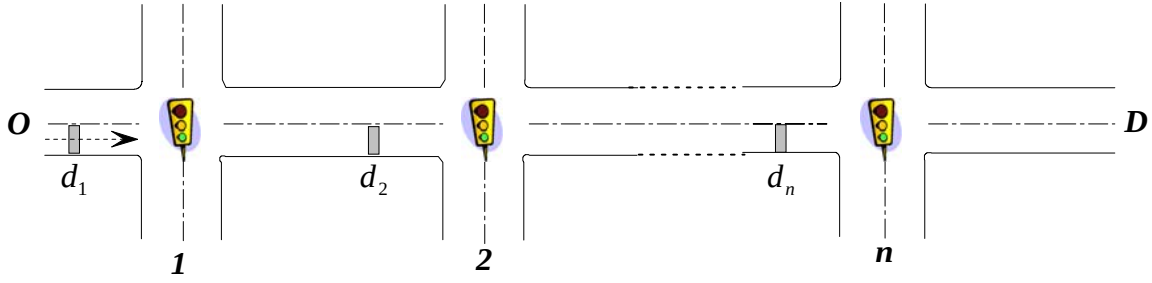


Figure 2. Geometric Layout of Arterial Signal System

3.2 Arterial Travel Time Estimation Model

The difficulty of estimating travel time on arterials comes from the interrupted nature of traffic flows at intersections of urban street. To estimate the arterial travel time, we first decompose the arterial into links, and for each link the tail node is the upstream intersection and the head node is the immediate downstream intersection. Arterial travel time therefore can be estimated through the aggregation of link travel time and the travel time of each link is calculated based on the time of arrival. The link travel time can be further decomposed into two components, the free flow travel time t_0 and the intersection delay t_d . The free flow travel time t_0 can be calculated based on the travel distance and the travel speed under prevailing conditions without delay. The intersection delay t_d can be calculated by either the queuing delay t_q or signal delay t_s due to the red light, or the summation of the two. The queuing delay can be estimated at every time instant with second-by-second volume data of the advance detector and signal discharging rate. Also, the signal delay due to the red phasing can be measured with corresponding signal status data. With the time dependent queuing delay and signal delay at the intersections along the corridor, the link travel time can thus be estimated and the arterial travel time is the recursive aggregation of time-dependent link travel time.

To better illustrate the arterial travel time calculation, we assume that a dummy vehicle is being sent from the origin O to the destination D . We then trace the dummy vehicle to calculate its delays at every intersection at the time of arrival. The detail of the estimation algorithms is discussed next.

- **Free Flow Travel Time Estimation**

The free flow travel time is the vehicle travel time under un-congested status or prevalent condition. Usually, it can be roughly calculated from the distance and the speed limit. However, the typical travel speed is slightly higher than the speed limit when traffic is light. Studies from recent research found that the vehicle speed on arterials tends to be constant for un-congested traffic (19). Therefore it is reasonable to use the average travel time speed measured at off-peak hours to calculate the “free flow travel time” t_0 in this research.

- **Intersection Delay Estimation**

The intersection delay consists of two components: queuing delay and signal delay. Assuming that the yellow and all-red intervals can be counted as green time, and then any moment when a vehicle approaching the intersection, the dummy vehicle will meet two alternative signal states: green time that the vehicle can continue to move, or red time that the vehicle must stop to wait. Since we separate the calculation of free flow travel time with intersection delay, the link traversal time is zero for the dummy vehicle if no intersection delay occurs. There are mainly four cases for the calculation of the intersection delay according to the vehicle arrival time at the intersection.

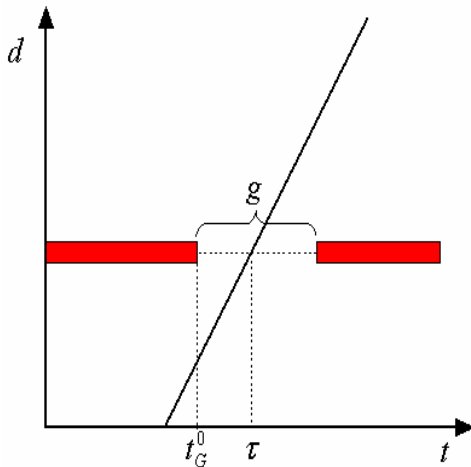


Figure 3(a) No Delay

Figure 3(a) shows the situation when a vehicle arrival event is triggered in the green phase before the phase ending time $t_G^0 + g$, where t_G^0 is the green phase starting time and g is the green phase duration. Both the queuing delay and the signal delay are equal to zero, because there is no standing queue before the stop line and the green phase will allow the vehicle passing the intersection without any delay. The intersection delay at time instant τ can thus be calculated based on Equation 1(a).

$$t_d(\tau) = 0 \quad (\tau \leq t_G^0 + g) \quad (1a)$$

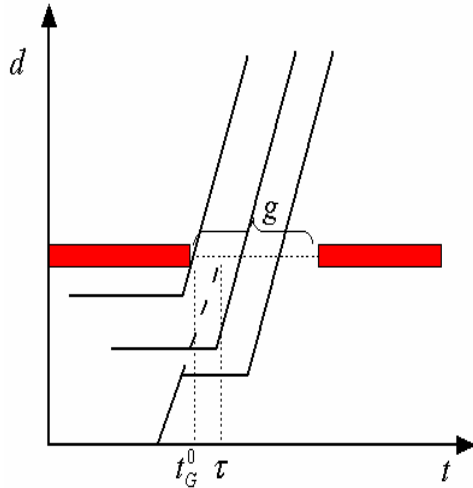


Figure 3(b) Queuing Delay

In [Figure 3\(b\)](#), the vehicle also arrives at the intersection before the green phase ending time $t_G^0 + g$. However, different with the case depicted in [Figure 4\(a\)](#), there are standing queue stored before the stop line. In this case, the vehicle can still pass the intersection during the current green phase, but encounter a queuing delay t_q . The intersection delay at time instant τ is equal to the queuing delay as presented in [Equation 1\(b\)](#).

$$t_d(\tau) = t_q(\tau) \quad (\tau \leq t_G^0 + g) \quad (1b)$$

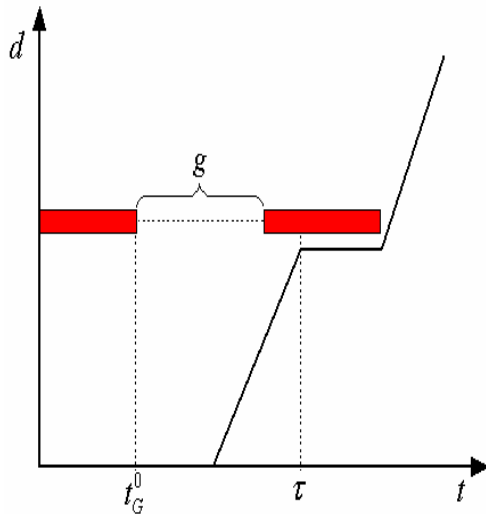


Figure 3(c) Signal Delay

When a vehicle arrival event occurs after the green phase ending time $t_G^0 + T_G$ as shown in [Figure 3\(c\)](#), the vehicle will experience the delay because of red light. In such case, assuming the vehicle is the first vehicle waiting at the stop line, thus there is no queuing delay for the vehicle; however, the subject vehicle will suffer the signal delay t_s , and wait until next green phase to pass the intersection. The intersection delay at time instant τ is thus equal to the signal delay as shown in [Equation 1\(c\)](#).

$$t_d(\tau) = t_s(\tau) \quad (\tau > t_G^0 + g) \quad (1c)$$

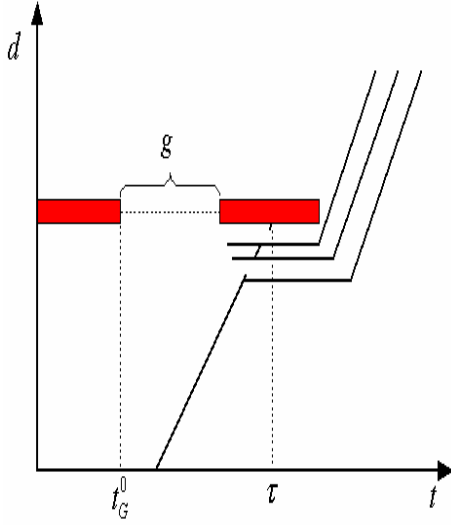


Figure 3(d) Signal & Queuing Delay $t_d(\tau) = t_q(\tau) + t_s(\tau) \quad (\tau > t_G^0 + g) \quad (1d)$

In the last case depicted in Figure 3(d), a vehicle arrives after $t_G^0 + T_G$ with queue ahead, the intersection delay is the queuing delay t_q plus the signal delay t_s as presented in Equation 1(d). An special case occurs when the approach is oversaturated, the green phase can not clear all the queuing vehicles, and the intersection delay suffered by the vehicle is also $t_q + t_s$, but t_s is longer than one cycle.

The queuing delay $t_q(\tau)$ is the time required to clear the queuing vehicles between the subject vehicle and the stop line at time τ , it can be estimated as Equation 2 based on the number of vehicles in the queue (20).

$$t_q(\tau) = l_l + h \times n_q(\tau) \quad (2)$$

where l_l is the start-up lost time, h is the saturation headway, and $n_q(\tau)$ is the number of vehicles in the queue at time τ , which can be calculated as the difference of the arrival counts and the departure counts. The arrival count can be measured by the advanced detector, but the true departure count is unknown without the stop line detector installed. However, the number of queuing vehicles can be roughly estimated as shown in Equation 3, assuming the queue will not back up over the advanced loop detectors.

$$n_q(\tau) = \begin{cases} \max\{0, A(\tau) - D(t_G^0) - s \times (\tau - t_G^0)\}, & \text{when green is on} \\ A(\tau) - D(t_G^0 + g), & \text{otherwise} \end{cases} \quad (3)$$

where

$n_q(\tau)$ is the number of vehicles in the queue at time τ ;

$A(\tau)$ is the arrival count at time τ ;

t_G^0 is the start of the green time of current cycle;

s is the saturation flow rate;

g is the green time of the current cycle;

$D(t_G^0)$ and $D(t_G^0 + g)$ are the departure counts at the start of the current green, and the end of the current green, respectively.

The signal delay $t_s(\tau)$ is the duration for the red phase. Since the signal status change can be acquired from the on-site controllers, the signal delay can thus be calculated by measuring the remaining red phase time of the cycle as [Equation 4](#).

$$t_s(\tau) = \begin{cases} 0, & \text{when green is on} \\ t_G^0 + g - \tau, & \text{otherwise} \end{cases} \quad (4)$$

• **Time-dependent Travel Time Estimation**

The time-dependent travel time along the arterial road is the recursively aggregation of the free flow travel time t_0 and intersection delay (i.e. queuing delay t_q and signal delay t_s) along the corridor. However, the queuing delay t_q and signal delay t_s are different at different time intervals, and it can not be simply summed up based only on the starting time from the origin. The queuing delay and signal delay should be calculated according to the time interval that the vehicle arrival at the corresponding intersections. Therefore, the time-dependent travel time can be calculated as [Equation 5](#).

$$t^{O \rightarrow D}(T^O) = \sum_{i=0}^n t_0^{i \rightarrow i+1} + \sum_{i=1}^n t_q^i(T_{arrive}^i) + \sum_{i=1}^n t_s^i(\hat{T}_{arrive}^i) \quad (5)$$

where,

$t^{O \rightarrow D}(T)$ is the estimated travel time from origin O to destination D if the vehicle starts the travel at time instant T ;

T^O is the starting time when the dummy vehicle start the travel from the origin O ;

$t_0^{i \rightarrow i+1}$ is the free flow travel time measured under un-congested traffic from the upstream Intersection i to the downstream Intersection $i+1$;

$t_q^i(T)$ is the queuing delay that will be suffered by the vehicle at Intersection i when the vehicle approaching the intersection at time instant T ;

T_{arrive}^i is the arrival time instant at Intersection i , which can be calculated from [Equation 6](#);

$$T_{arrive}^i = T_{depart}^{i-1} + t_0^{i-1 \rightarrow i} \quad (6)$$

T_{depart}^i is the departure time instant at Intersection i , which can be calculated from Equation 7;

$$T_{depart}^i = T_{arrive}^i + t_q^i(T_{arrive}^i) + t_s^i(\hat{T}_{arrive}^i) \quad (7)$$

$t_s^i(T)$ is the signal delay will be suffered by the vehicle at Intersection i when the vehicle approaching the intersection at time instant T ;

$\hat{T}_{arrive}^i$ is the adjusted arrival time at Intersection i for signal delay calculation, it depends on the signal and flow status at the intersection. If the green time can clear all the queuing vehicles, $\hat{T}_{arrive}^i = T_{arrive}^i$, otherwise, $\hat{T}_{arrive}^i = T_{arrive}^i + t_q^i$.

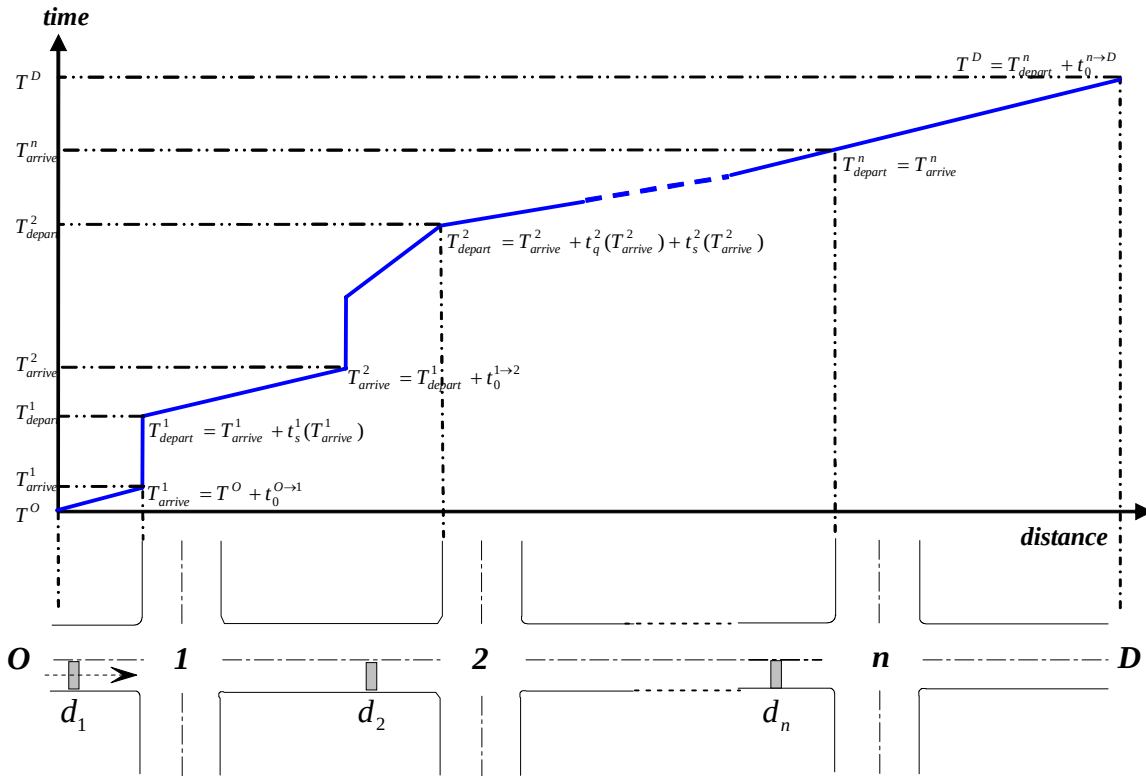


Figure 4. Vehicle Trajectory along the Corridor

Figure 4 demonstrates the trajectory of a dummy vehicle that starts the travel from the origin O at time instant T^O . It is assumed that the vehicle meets Case (c) described above when it arrives at Intersection 1, i.e. no queuing vehicles at the stop-line, but the signal is

red. Its arriving time T_{arrive}^1 at Intersection 1 is $T^O + t_0^{O \rightarrow 1}$, and the departure time is $T_{arrive}^1 + t_s^1(T_{arrive}^1)$. Traveling to the next intersection, the Intersection 2, the vehicle meets the Case (d). Both queuing delay and signal delay occur when the vehicle arrives at Intersection 2 at time instant $T_{arrive}^2 = T_{depart}^1 + t_0^{1 \rightarrow 2}$. In this case, the demo vehicle first suffer the signal delay $t_s^2(T_{arrive}^2)$, and then the queuing delay $t_q^2(T_{arrive}^2)$. The vehicle keeps running to the last Intersection n at time instant T_{arrive}^n , when it meets Case (a) and passes the intersection without any delay. It arrives at the destination D at time T^D as described in Figure 4, and the travel time for this vehicle is $t^{O \rightarrow D}(T^O) = T^D - T^O$.

4. Performance Test and Analysis

4.1. Example Problem

In this research, the proposed methodology is tested under the computer simulation environment. The microscopic simulator PARAMICS V5 developed by Quadstone (21) is selected as the testing tool. An additional simulation plug-in for actuated signal control is added to ensure the functionality of actuation signal control (22). The second-by-second detector data and corresponding signal status data can be acquired, the travel time along the testing corridor can thus be estimated at each time interval using the proposed methodology.

The simulated network is a hypothetical arterial network consisted with 22 zones and 10 actuated signalized intersections as shown in Figure 5. The length of the east-west direction is about 2.5 miles. To provide a desirable environment, it is assumed no interlink sources or sinks between the links connecting the intersections. For the purpose of preliminary testing, the simulation time is 90 minutes from 7:45 am to 9:15 am with its first 15 minutes used for warm-up. The morning peak hour results from 8 am to 9 am are generated and analyzed.

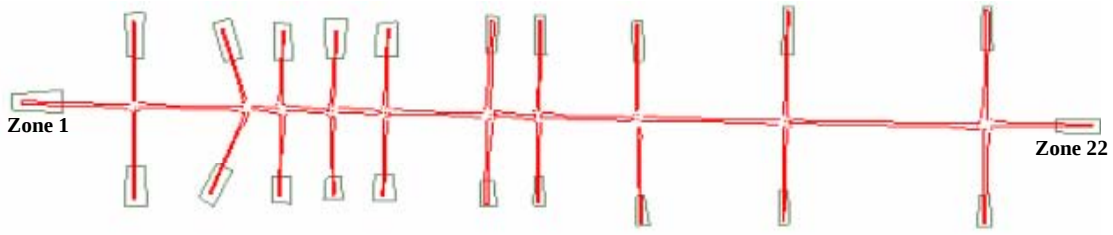


Figure 5. Example Hypothetical Arterial Network

4.2. Results Analysis

The Root Mean Squared Percent Error (*RMSP*), a widely used error measure that can provide a fairly good initial estimate of the degree of fit between the simulated and the actual traffic measurements, is applied to verify the results of the proposed model as Equation 8.

$$RMSP = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{\hat{x}_i - x_i}{\hat{x}_i} \right)^2} \quad (8)$$

where *RMSP* is the root mean squared error, x_i is the i^{th} simulated traffic measurement value, and $\hat{x}_i$ is the i^{th} actual traffic measurement value.

Figure 6 shows the aggregated 15-seconds-interval travel time for vehicles traveling along the example corridor during the morning peak hour. Figure 6(a) is the eastbound travel time from zone 1 to zone 22. Each pink data point in the figure represents the estimated corridor travel time of the vehicles departing from zone 1, and the blue data point represents the corresponding measured real travel time. Figure 6(b) depicts the westbound travel time from zone 22 to zone 1. From the figures we can see that the travel times generated from the proposed model have a good match with the actual ones at both eastbound and westbound directions. As the preliminary result shows, the statistic measure *RMSPs* for eastbound and westbound travels are 0.0613 and 0.0702 respectively, which are very small and in the acceptable range. The average travel time within the morning peak hour is 310.8 second for the eastbound movements and 302.5 second for the westbound movements.

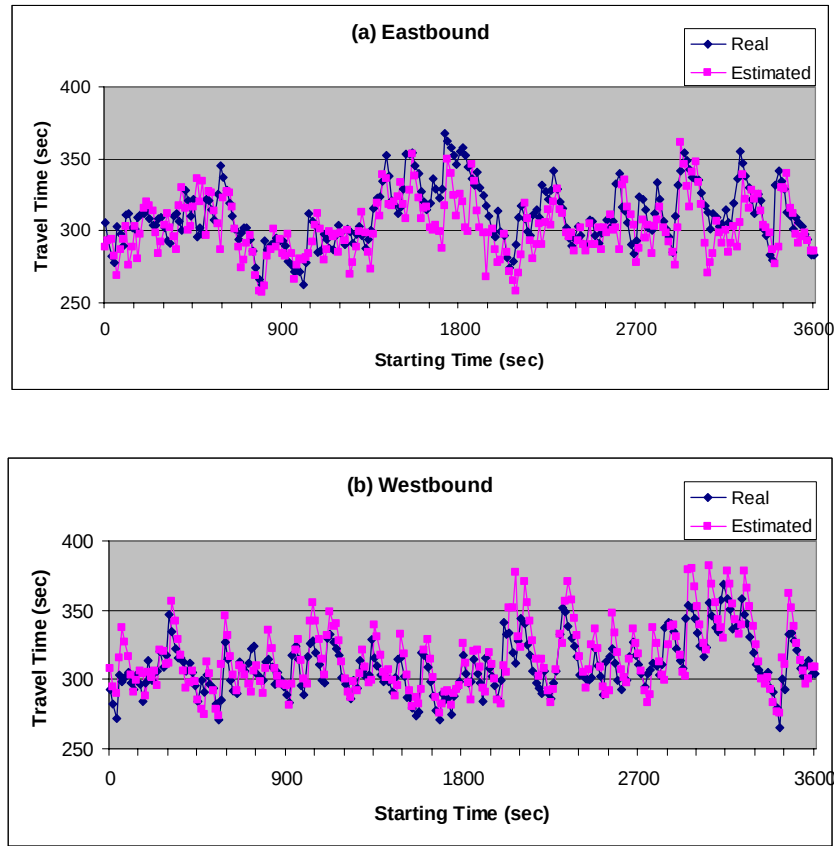


Figure 6. Estimated Travel Time V.S. Real Travel Time along the Corridor

To further testing the reliability of the proposed model under different traffic conditions, the example network is investigated with various travel demand loadings, which are 0.8, 0.9, 1.0, 1.1 and 1.2 times the original peak-hour demand. The results are summarized as shown in [Table 1](#). From the table we can see that all statistic *RMSPs* are within acceptable range less than 0.1, which indicates that the proposed model have good estimation on arterial travel time. Meanwhile, the table shows that the average travel time along the corridor is increasing as the demand loading increase. It is also reasonable because the traveling vehicles will suffer higher cost as the network becoming congested.

Table 1. Model Performance with Various Demands Loading

	Eastbound		Westbound	
	<i>RMSP</i>	Average Travel Time	<i>RMSP</i>	Average Travel Time
0.8	0.0564	293.8	0.0633	295.1
0.9	0.0626	297.9	0.0620	295.0
1.0	0.0612	310.8	0.0702	302.5
1.1	0.0685	313.8	0.0901	317.5
1.2	0.0778	330.1	0.0941	343.0

5. Concluding Remarks and Further Research

The traffic time estimation model proposed in this paper calculates the time-dependent arterial travel time based on the data from existing signal controllers and vehicle detection systems. The major advantage of this work comparing with some of the previous studies is that this research fully utilizes all available traffic information, including not only the detector data but also the corresponding signal status data, to process the estimation. Therefore the model can be implemented under various traffic conditions, and can generate accurate results even to congested arterials. The model proposed can also adapt to different signal controllers, fixed-timing, vehicle-actuated signal, or adaptive signal. The requirement is to collect the second-by-second data from advanced loop detectors and on-site signal controllers. Although the simulation study of a simple real network presented in this paper is limited, the results generated are reasonable and promising.

Considering any laboratory model and project should progress toward actual field implementation, the software-only environment should be followed and extended to a hardware-in-the-loop simulation in which the emulated traffic controller logic is replaced with a real controller. This will allow using all of the controller's true functionalities instead of the limited subset of standard features that is supported by the simulation package.

This research serves as a starting point of a long-term research effort undertaken by the authors to develop a systematic approach to collect, monitor, diagnose, fine-tune and audit the state-of-the-practice closed-loop signal control systems. The immediate goal of this project is therefore to develop an online performance measurement system for signalized arterials, and a logical next step is to develop methodologies to utilize the real time and archived arterial performance for the improvements of traffic operation, planning and traveler information systems.

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