Real-Time High-Resolution Data Logging and Performance Monitoring Device for Signalized Intersections

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ABSTRACT

Real-time monitoring of traffic signal system operations can be accomplished through the central or closed loop software that communicates with the traffic signal controllers in the field. However, there are a few significant limitations with this approach. This paper presents an alternative approach to improve real-time monitoring of signalized intersections operations using instrumentation at each signalized intersection cabinet. An intelligent data acquisition device has been developed to provide real-time high-resolution data logging and performance monitoring for signalized intersections. The device was tested and validated in the lab using a hardware-in-the-loop simulation model. The simulation data were collected from an isolated intersection in the city of Moscow, Idaho.

Keywords: Data Logging Device, Real-Time Monitoring, Modeling and Simulation, Measure of Effectiveness, Delay Estimation.

1. BACKGROUND

In integrated traffic signal systems, real-time monitoring can be accomplished through the central or closed loop software that provides control decisions and continuously communicates with the traffic controllers and cabinets. These control software tools use detector and signal status data to estimate different performance measures for each movement and for the intersection. There are a few significant issues with this approach. The type and quality of the measure of effectiveness (MOEs) reported depend on the control software and on the configuration of the detection system used in the field. In addition, only average values are usually collected and reported. Furthermore, data retrieved by the closed loop or central system are not typically accessible to users. For traffic signal systems that have no control software, real-time monitoring can only be done by accessing the MOEs collected and stored in the traffic controller. System operators have to access these controllers and manually download this data every time interval.

An alternative to achieve real-time monitoring is to use instrumentation at each cabinet that is connected to actuator and detector signals. The data that can be monitored are not limited by what data are collected or the frequency at which they are collected by the closed loop, central system software, or traffic controllers. The intelligent data acquisition device [1] is able to provide real-time high-resolution data logging and performance monitoring for signalized intersections. It can be embedded in the signal cabinet and executes data tabulation logic and writes the status of all I/O channels to a data file that is remotely accessible through IP based communication.

2. DATA LOGGING DEVICE

Components and Communication Architecture

Figure 1 shows the proposed data logging instrumentation and its major components. This instrumentation is based upon the “Opto 22” family of ultimate I/O brains (Item 10 in Figure 1) and “SNAP IDC 5” modules (4 Channel 10-24 VDC Inputs - item 3 in Figure 1).

The data logging device components include:
- wiring harness that connects to the 24 volt terminals (item 1);
- wiring harness that terminates on the modular connector of the IDC 10-24 module (item 2);
- IDC 10-24 modules monitoring different functions in the cabinet (items 3, 4, 5, 6, and 7);
- power supply for the Ultimate I/O Brain Module (item 8);
- serial connection for updating the firmware (item 9);
- 10/100 BaseT connection for Ethernet IP access (item 10).

Connecting the Data Logging Device to Different Cabinets Assemblies

In a standard NEMA TS1 style cabinet, the connections to the controller are made through the connection matrix on the back panel of the cabinet. The proposed connection is shown in
Figure 2. The data logging device cables should have non-locking fork terminals that can be connected to the matrix. The connection is done by loosening the screws on the back panel then connecting the data logging device cable terminals.

**Figure 2 Proposed Data Logging Device Connection to NEMA TS1 Cabinets**

In a NEMA TS2 Type 1 style cabinet, the data logging device connection is rather challenging as the cabinet assembly does not have connection matrix. The controller communicates with the cabinet using a serial connection through the cabinet’s BIUs. The communication link from the controller uses the RS-485 serial communication format or synchronous data link control (SDLC) in combination with the NEMA standard TS2 command frames. There are two possible connection options. The first option is to connect via the data logging device to the terminals on the back panel of the cabinet. The second option is to connect the cabinet’s BIUs that are hardwired to this back panel. This will likely require cooperation with the cabinet vendors as details of BIU wiring mechanism are needed. The first mode of connection is represented uses a solid line and the second mode is represented uses dashed lines in Figure 3.

**Figure 3 Two Proposed Data Logging Device Connection Options to TS2 Type 1 Cabinet**

As shown in Figure 4a and 4b, there are two options to connect the data logging device in a NEMA TS2 Type 2 style cabinet since this cabinet combines standards for the TS1 and TS2 Type 1. The first is to connect the device to the connection matrix on the back panel, like that of the NEMA TS1 cabinet. The second is through a serial connection through either the cabinet’s back panel or the BIUs similar to that for TS2 Type1 cabinets.

**Output Files**

The data logging device monitors and records the communication exchanged between the detector and the controller and between the controller and signal heads. It also records any other special calls sent to the controller such as pre-emption calls. In essence, the device monitors activities in all input and output communication channels to and from the controllers. In each sampling interval, it scans the status of all input/output channels and records the state of each channel (on or off). The data are then stored in a log file which can be accessed through the Ethernet port. The sampling interval for data logging can be as small as 10ms.

Data recorded by the data logging device include date, time, and the status of each communication channel on the sampling interval. Figure 5 shows a sample of the data logging device files for the status of detector and signal indication I/O communication channels. A value of “-1” represents when the communication channel is “On”; a value of “0” represents when the communication channel is “Off.”

**Figure 4 Proposed Data Logging Device Connection to TS2 Type 2 Cabinet**

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<th>Time</th>
<th>Ph1_Veh_Call</th>
<th>Ph2_Veh_Call</th>
<th>Ph1_Veh_Call</th>
<th>Ph2_Veh_Call</th>
<th>Ph1_Veh_Call</th>
<th>Ph2_Veh_Call</th>
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<tbody>
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**Figure 5 Sample Data Logging Device Files**

a. Status of Detector Input Channels
### 4. RESEARCH METHODOLOGY AND EXPERIMENTAL DESIGN

#### Proposed Delay Estimation Method

Two different delay estimation methods are used in this paper. The first [7] is based on the Webster delay equation, a commonly used model to determine the average control delay of an intersection approach. The Webster delay equation has three terms. The first term presents the average delay for a particular approach assuming uniform arrivals at a fixed-time signal-controlled intersection and can be easily derived using deterministic queuing theory. The second term is added to account for random arrivals. The third term is subtracted from the first two terms and varies from zero to a value equal to the second term. The Webster delay equation is given as follows:

\[
D = \frac{C(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)} - 0.65 \frac{C}{q^2} x^{1.2} x^{(2+\Delta)}
\]  

where

- \(D\) = Average control delay (seconds/vehicle);
- \(C\) = signal cycle length (seconds);
- \(x\) = degree of saturation;
- \(q\) = volume (vphs); and
- \(\lambda\) = effective green proportion.

Parameters \(C\) and \(\lambda\) are obtained from the signal timing data. Volume, \(q\), is directly obtained from the detector measurement. The degree of saturation, \(x\), should be calculated based on detector occupancy and signal timing data. A stop-line detector is required to collect flow and occupancy measurement.

The second delay estimation method examined in this study uses the analytical model proposed by Skabardonis and Geroliminis [2]. In this model, the delay under saturation is the sum of two types of delay: delay caused by the traffic signal and delay caused by the queue present in the intersection approach.

The first part of the model assumes that each vehicle has no interaction with other vehicles in the traffic stream. Under this assumption, all queued vehicles are considered stopped at the stop line (vertical queue). The delay, \(d(t)\), of a single vehicle as a function of arriving time, \(t\), is given by Equation (2):

\[
d(t) = r - T - \frac{u_f}{2\gamma_d} t + \frac{u_f}{2\gamma_s} t
\]

where

- \(r\) = the effective red time;
- \(T\) = the reaction time;
- \(u_f\) = free flow speed;
- \(\gamma_d\) = deceleration rate;
- \(\gamma_s\) = acceleration rate; and
- \(t\) = the time a vehicle starts to decelerate.

The parameters for \(\gamma_d\), \(\gamma_s\), \(u_f\), and \(T\) are assumed constant. Their values are determined according to the Institute of Transportation Engineers (ITE) guidelines. The effective red time, “\(r\)”, is directly obtained from signal timing data reported in the data logging device output files. The parameters for \(u_f\) and \(t\) are obtained from detector measurements.
The delay in the second part of the Skabardonis and Geroliminis model is the result of the queue present at the traffic signal approach. It is estimated based on the kinematic wave theory considering the temporal and spatial formation of the queue and assuming a relationship between linear flow and density. The delay for the n-th vehicle arriving at the signal from the beginning of the red time is the sum of three types of delays (\(d_{q1}, d_{q2}, d_{q3}\)) as illustrated in Figure 6.

\[
d_{q1} = \left(\min(n, N_{qm}) - 1\right) \frac{L_q}{u_f}
\]

\[
d_{q2} = -\left(\min(\max(n, N_{qm}), N_q) - N_{qm}\right) \frac{L_q}{u_w}
\]

\[
d_{q3} = \left(\min(n, N_q) - 1\right) \frac{L_q}{w}
\]

where

- \(L_q\) is the effective length of a stopped vehicle;
- \(u_w\) is speed of the shockwave;
- \(w\) is congested wave speed;
- \(N_{qm}\) is number of the maximum queue;
- \(N_q\) is number of the maximum back of the queue.

The effective length of a stopped vehicle \(L_q\) is assumed constant using the reciprocal of the jam density \(k_j\). The parameters \(u_f\), \(u_w\) and \(w\) are obtained from flow and occupancy measurements based on an assumed linear flow-density relationship shown in Figure 7.

The parameters of \(N_{qm}\) and \(N_q\) could be calculated using equations (6) and (7).

\[
L_{qm} = r \frac{u_f u_w}{u_f + u_w} \quad N_{qm} = \frac{L_{qm}}{L_q}
\]

\[
L_q = r \frac{W U_w}{W - U_w} \quad N_q = \frac{L_q}{L_q}
\]

### Hardware-in-the-Loop Simulation Model

The data logging device was tested and validated in the lab using a hardware-in-the-loop simulation model, in which the control of the intersection in the simulation model was done by an actual traffic controller. A controller interface device (CID) was used to facilitate the information exchange between the microscopic simulation model and an actual traffic controller. Detector actuation information was sent from the simulation model to the controller. Signal status information was sent back from the controller to the simulation model. This data exchange was done in every simulation time step. In this experiment, VISSIM microscopic simulation was used along with a NEMA TS2 traffic controller. The data logging device was connected to the controller through an interface connected to the A, B, C, and D connectors in the traffic controller. The data flow in the hardware-in-the-loop simulation model used in the analysis is shown in Figure 8. The simulation time step was set to 100 ms (0.1 second).

![Figure 8 Hardware-in-the-loop Simulation Model](image_url)
acceptable level of accuracy using the high-resolution logging device output data.

5. ANALYSIS AND RESULTS

Delay values reported by the VISSIM simulation model were compared against values estimated using the data logging device output files and following procedure described in section 4. The delay value of each cycle was calculated. Cycle-delays were then aggregated over the 15-minute simulation time. Mean absolute error and mean percent absolute error values for each simulation run were used to compare the accuracy of the estimated measurements to true values obtained from VISSIM simulation output.

Figure 10 shows the comparison of the true delay (simulated) and delay values estimated using the Webster formulation over 25 runs. Simulation runs with five different traffic volume levels were performed: 400 vph, 500 vph, 600 vph, 700 vph, and 800 vph.

The accuracy of estimated delays was analyzed using the mean absolute error and mean absolute percent error shown in Figure 11a and Figure 11b. The results indicate that the maximum absolute errors for flow rates of 400 to 700 vph are less than 5.0 seconds/vehicle and that the average error value is approximately 2.0 seconds/vehicle. The maximum percent errors are less than 20.0 percent with an average value of approximately 6.0 percent. The error increased significantly as demand increased to 800 vph (near or over saturation). This is expected as Webster equation is primarily used to determine delay values for under-saturated conditions (volume to capacity ration of less than 0.8).

Figure 9 VISSIM Simulation Network

Figure 10 Comparison of Simulated and Estimated Delay Estimation

The second method to estimate delay in this study is based on the analytical model proposed by Skabardonis and Geroliminis. A sample of comparisons of simulated and estimated average delay is presented in Figure 12.

One limitation of this method is that it requires the maximum queue length not to extend to the upstream detector location. In
In this study, the detector was placed approximately 180 feet upstream of the stop bar. Initial investigatory simulation runs showed that, when the traffic volume exceeds 500 vph, the maximum queue length exceeded the upstream detector location. Accordingly, only three traffic flow levels: 300 vph, 400 vph and 500 vph were used in the analysis.

The maximum absolute error for 300 vph is less than 1.0 second/vehicle. The maximum error values for volumes of 400 vph and 500 vph are less than 2.0 seconds/vehicle (Figure 13a). All percent absolute errors are within 6.5 percent (Figure 13b). This approach predicts delay with higher accuracy than the Webster method.

![Mean Absolute Error](image1)

**a. Mean Absolute Error**

![Mean Absolute Percent Error](image2)

**b. Mean Absolute Percent Error**

**Figure 13 Mean Absolute Error and Mean Percent Absolute Error (Method 2)**

In summary, under unsaturated flow conditions, the maximum delay error is approximately 5.0 seconds/vehicle, and the average delay error is approximately 2.0 seconds/vehicle. From an operational perspective, these variations are within acceptable ranges. These values show that average delay values can be accurately estimated using the high-resolution output data reported by the data logger device.

6. **SUMMARY AND CONCLUSION**

The paper presents a high-resolution data logging device that can be used in real-time traffic monitoring at signalized intersections. The data logging device can be connected to traffic cabinets using different connection modes. It records the communication exchanged between the detector and the controller and between the controller and signal heads. The data logging device main function is to log and store the status of all input and output communication channels at every time step, which can be as small as 10 milliseconds. The data logging device can be accessed remotely through an Ethernet port over IP based communication protocols. It provides an opportunity for high-resolution real-time performance monitoring of intersection operations. In this paper, the application to demonstrate how the data logging device can be used to monitor intersection operations involves macroscopic estimation of average delay values using data logging device output. The results presented that the data logging device output can be used to accurately estimate average delay values for signalized intersection approaches.

7. **REFERENCES**


