IMPROVEMENTS TO A QUEUE AND DELAY ESTIMATION ALGORITHM UTILIZED IN VIDEO IMAGING VEHICLE DETECTION SYSTEMS

A Thesis Proposal

By

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INTRODUCTION

Video imaging vehicle detection systems (VIVDS) are steadily becoming the preferred method for the detection of vehicles at signalized intersections. The use of VIVDS are progressively replacing detectors such as inductive loop detectors at signalized intersections due to the high cost of maintenance and frequency of repair involved with these systems. There is a need for real-time queue and delay estimation of vehicles at signalized intersections, as often times, modern traffic signal controllers are able to use these real-time data in order to optimize intersection performance. Accordingly, the queue and delay estimation algorithm (QDA) has been developed by researchers at the Texas Transportation Institute (TTI) in order to procure reasonable estimates of queue length and delay, while minimizing noise associated with measured queue length estimates collected by VIVDS hardware.

Current mathematical techniques used in the QDA involve a weighted average of previous and current estimates of queue length in order to procure output queue length estimates. However, the initial algorithm that was designed presents a mathematical bias, whereby estimates output from the QDA are inherently low. This is due to the current logic used by the QDA intended to minimize the effects of errant and dropped detections. Errant data or data containing a high degree of variability offers little justification for the use of this video detection technique over other forms of detection. Therefore, the improvement of the QDA for VIVDS application is necessary before this method can be relied upon in order to provide accurate estimates of queue length and delay.

PROBLEM STATEMENT

A subtask for the National Cooperative Highway Research Program (NCHRP) project 3-79 investigated non-intrusive methods for detecting vehicles and estimating performance measurements at signalized intersections using VIVDS. This subtask specifically investigated the performance of signalized intersections using queue length and delay as the primary MOEs. Thus, the QDA was developed in response to the objectives proposed in this subtask. The QDA estimates MOEs in real-time using current and previous estimates of queue length. However,
this method of queue length estimation using the QDA was hindered by a bias in the mathematical procedure used to estimate MOEs.

Due to the shortcomings of the initial versions of the QDA, it is desired to modify the QDA such that the estimation of queue length output from the QDA does not bias queue length estimates. The modification of the QDA must include the implementation of a mathematical technique that allows for real-time queue length estimation based on previous and current estimates, while maintaining an unbiased output. Eliminating this bias is essential for accurately estimating queue length, as well as estimating delay at a signalized approach. This research intends to investigate mathematical procedures that satisfy the needs for real-time estimation and eliminate the bias in queue length and delay estimation. Furthermore, it is desired to develop a new version of the QDA that does not underestimate queue length as does the current version.

RESEARCH OBJECTIVES

The research goal is to identify the best mathematical technique for minimizing the bias in queue length estimation output from the QDA using VIVDS. Furthermore, this goal will be accompanied by an improved estimate of delay, which is dependant upon an accurate estimate of queue length. The specific objectives of this research are as follows:

- Evaluate various methods for minimizing noise in queue length data collected using VIVDS and analyzed using the QDA.
- Determine which mathematical technique minimizes noise with respect to queue length estimation using the QDA. Inherently, this approach should also determine which mathematical technique minimizes noise with respect to delay estimation at a subject approach.
- Implement the best mathematical technique for queue length and delay estimation in the QDA.

BACKGROUND

Non-intrusive queue length and delay estimation at a signalized intersection using VIVDS technology essentially uses a series of detectors placed incrementally from the stop-line of a subject approach. In its simplest form, the actuation of one of these detectors indicates the
presence of a vehicle corresponding to the detector’s placement from the stop-line. Moreover, the successful actuation of the furthest detector from the stop-line at the instant the QDA polls the VIVDS hardware for current information, represents the queue length at that polling interval.

The design of the queue and delay estimation algorithm (QDA) is such that the information output from the QDA can be used for various intersection optimization processes. The QDA could be used for processes involving adaptive control of a signalized intersection. Furthermore, the QDA could also be used to give priority to approaches requiring additional green time or the elimination of a phase on minor approaches in order to accommodate traffic on the major approaches ([1]).

**VIVDS Sensor Layout**

A typical VIVDS sensor layout for queue detection can be seen in Figure 1. Each horizontal bar in Figure 1 represents a detector placed at a pre-determined distance from the stop-line. This setup consists of eight distinct detection zones placed at distances such that queue lengths of 50, 100, 150, 200, 250, 300, 350 and 400 ft can be output from VIVDS to the QDA ([1]).

When vehicles begin to accumulate at a signalized intersection, the QDA is allowed to report queue length once a detector has been switched “on” for a certain period of time. Hence, detectors function on a delay such that vehicles must be present on a detector for a specified duration of time in order to place a call to the VIVDS controller. Queues are estimated by the QDA once the QDA obtains information corresponding to the phase status from the traffic signal controller. When the indication is red on a subject approach, the QDA is able to use detector information and utilize this data to establish queue length estimates. Also, the QDA contains logic whereby a combination of the most distant detector and detectors located at the beginning of the queue must be switched “on” in order to report queue length. This logic helps the QDA avoid reporting erroneous queue length estimates due to perhaps a malfunctioning detector.

Queue length is reported to an industrial computer containing the QDA every 10 seconds. Queue length is defined as the distance associated with the farthest detector that is switched “on” at the
instant a 10 second interval initiates. The QDA then combines data from the detector zone outputs with traffic signal phasing data in order to estimate queue length ($L$). Therefore, the QDA can obtain information from the traffic signal controller indicating that the traffic signal on the subject approach is displaying a red indication. Once this information is received, the QDA is able to assume that vehicles will begin to queue as vehicles arrive at the approach.

![Figure 1 Typical VIVDS Setup for Queue Detection ($L$)](image)

**Current Queue Logic during the Queue Growth Period**

The queue growth period includes the time period starting at the beginning of a red indication, and continues into the first few seconds of a green indication ($L$). During this time period, vehicles begin to accumulate and begin to form a queue growing back from the stop-line. The QDA currently estimates the queue length at 10 second intervals during the queue growth period. However, due to sensitivity issues involving the VIVDS hardware and erroneous detections that occasionally occur during detection, the furthest reporting detector by VIVDS does not always provide the most reliable estimate of queue length. Therefore, current logic used for queue estimation utilizes a weighted average based on previous and current estimates of queue length to
ultimately produce a QDA estimated queue length. The following equation illustrates the weighting procedure currently utilized by the QDA.

\[
Q_i = Q_{i-1}(1 - f) + q_i f
\]

(Equation 1)

where;

\( Q_i \) = best-estimate of queue length during current period “i”, ft,

\( Q_{i-1} \) = best estimate of queue length from previous period, ft,

\( q_i \) = detected queue length estimate from queue detectors during current period “i”, ft,

and

\( f \) = weight given to the current queue length estimate (empirically calibrated).

The use of the weighted average technique essentially introduces three estimates of queue length. A previous estimate of queue length is established from the previous QDA output estimate stored within the QDA output file. This estimate represents the best estimate of queue length from the previous period, \( Q_{i-1} \). Next, the current estimate from the queue detectors, \( q_i \), represents the value obtained from the furthest actuated detector obtained from VIVDS. Lastly, these two values are weighted, and the current QDA output estimate, \( Q_i \), is produced. This result produces an intermediate estimate (i.e., an estimate that is not a multiple of 50) of queue length. This is believed to provide a more realistic, and potentially more accurate estimate of queue length than if an estimate that is a multiple of 50 were used, (i.e., if the QDA simply used \( q_i \) as the output).

As previously mentioned, this form of queue length estimation utilized by the QDA introduces a bias to the output queue length. The QDA output queue lengths are biased low due to the fact that the previous QDA output queue lengths are often smaller than currently detected queue lengths. Moreover, a “dropped” detection will often result in the QDA using the next smallest activated detector. This again results in an underestimated queue length that is less than ideal, and would not provide a reliable estimate due to the tendency of queues to grow over time.
Kalman Filters

In 1960 the creation of a mathematical filtering procedure for the optimization of discrete-data linear filtering problems was published by Rudolph Kalman. The filter was designed to provide recursive solutions to multiple-input, multiple-output systems intended to find optimal solutions based on noisy outputs (2). The appeal of the Kalman Filter involves this technique’s ability to minimize error in real-time associated with a system’s theoretical performance based on measured performance of the system collected at regular intervals. Furthermore, drastic improvements in computer technology around 1960 aided the widespread acceptance of the Kalman Filter for a multitude of applications and made this technique ideally suited for real-time estimation procedures (3).

The Kalman filter is designed to minimize the variance of the estimation error experienced during the output of a linear system. Accordingly, in order for a Kalman Filter to be implemented and to remove the noise of a system, the process must be described in linear terms (4). A linear system is simply the process that can be described by the following two equations involving the state equation (Equation 2), and the observed measurement equation (Equation 3) (3,5):

\[
x_{k+1} = Fx_k + w_k \\
z_k = Hx_k + v_k
\]

where:

\[x_k = \text{process state vector at time } t_k,\]
\[F = \text{matrix relating } x_k \text{ to } x_{k+1},\]
\[w_k = \text{assumed to be a white noise sequence with known covariance, } Q_k.\]
\[z_k = \text{vector measurement at time } t_k,\]
\[H = \text{matrix giving the ideal noiseless connection between the measurement and the state vector at time } t_k, \text{ and}\]
\[v_k = \text{measurement error, assumed to be a white noise sequence with known covariance, } R_k.\]
It is important to note that in the previously described mathematical procedure, that the white noise sequences for the state equation and the measurement equation are assumed to be normally distributed with means of zero.

It is easier to think of the Kalman Filter as a predictor-corrector algorithm. In this two-step algorithm, the predictor portion consists of a “time update” function that projects the current state estimate ahead in time. Next, the measurement update (corrector portion), adjusts the predictor estimate by an actual measurement at that time (see Figure 2).

![Figure 2 Kalman Filter Cycle (5)]

A more detailed diagram illustrating the Kalman Filter process can be seen in Figure 3. Within this figure, items denoted with a “hat” represent an estimate, and those denoted with a “super minus” represent a reminder that this value is a best estimate prior to assimilating the measurement at $t_k (3,5)$. In Figure 3, the matrix “$A$” relates the state at the previous time step, $k-I$, to the state at the current step, $k$. Also, the matrix “$B$” relates the optimal control input, $u$, to the state, $x$. Additionally, the variable “$I$” is an identity matrix, whereas the variables “$P_k$” and “$K_k$” represent error covariance and the Kalman Filter gain respectively.
The Kalman Filter has proven to be a reliable technique for obtaining optimal estimates. Furthermore, as time progresses, the filter relies more on measurements and less on initial assumptions. Therefore, the ability to obtain reasonably accurate estimates, as well as the proper calibration of the Kalman Filter with respect to estimates of white noise sequences and their respective covariance terms is essential for the successful implementation of the Kalman Filter.

**RESEARCH STUDY DESIGN**
The research objectives will be completed by following the procedure outlined in this section. The study design includes the following tasks, each of which is described in detail below.

1. **Review the Pertinent Literature:**
   A portion of the literature has been reviewed by the researcher prior to this proposal. A more thorough literature review involving previous applications of things such as Kalman Filters will be conducted by the researcher in the weeks to follow. Additionally, the researcher will review interim reports and documents pertaining to initial experimentation using the QDA. The researcher also intends to obtain literature related to queuing theory at signalized intersections. Lastly, the researcher will review literature pertaining to the functionality of the video detection hardware applied during this study, such that the researcher thoroughly understands the equipment utilized.
2. Collect Field Data

Much of the data collected for the purposes of this research were collected as part of a subtask for NCHRP 3-79, “Urban Street Performance Measurement: Prototype Non-Intrusive Detection Technique,” conducted at the Texas Transportation Institute (TTI). The research proposed is intended to improve upon the results of the previous research established in the preliminary phases of the NCHRP 3-79 subtask. Therefore, the data utilized during the proposed research will examine the same data sets.

Traffic Video From VIVDS Cameras

Video data from subject approaches were collected during the initial stages of the NCHRP 3-79 subtask and analyzed by TTI researchers. Collected data were obtained from a VIVDS camera facing the westbound approach at the intersection of George Bush Drive and Wellborn Road in College Station, Texas. The VIVDS camera is located at an approximate height of 25 ft and is capable of individual detection of all three lanes on the westbound approach. Video data from this camera were recorded and then transferred to DVD format for later analysis under laboratory conditions.

Ground-Truth Data

In order to analyze the capabilities and performance of the QDA and the VIVDS setup used for this study, it is necessary to collect ground-truth data representing the actual queue length at the subject approach (see Figure 4). These data were collected by placing video cameras adjacent to the subject roadway. Video cameras were positioned such that a 400 ft section of roadway could be examined along the subject approach and data pertaining to queue length and vehicle counts could be obtained.
Furthermore, data collected using the video cameras were collected concurrent with video data from the VIVDS system such that a comparison between actual queue data can later be compared to output from the QDA.

3. **Conduct Laboratory Experimental Procedures**

Much of this task was already completed during the initial phases of the NCHRP 3-79 subtask. This procedure reduces the field data that were collected and establishes detector placement for QDA analysis.

**Detector Placement and QDA Output Data**

A typical detector layout for queue detection used for this experimentation can be seen in Figure 1. Detectors were placed at distances of 50, 100, 150, 200, 250, 300, 350 and 400 ft. As the queue grows back from the stop-line, detectors activate based on the length of queue detected when vehicles are stopped on a given vehicle detection zone. When vehicles are present in a detection zone and the detector is activated for a time period that exceeds a designated delay time for that detector, a queue length will be recorded for the most distant detector that meets specified requirements for actuation. Furthermore, the QDA collects
queue data at 10 second intervals, whereby the most distant detector that is classified as “on” is recorded by the QDA.

Once data are collected by the QDA for the most distant detector for a given time interval, the QDA prepares an estimate of queue length. As mentioned in the Background portion of this proposal, often times detectors used in VIVDS are prone to occasional failure. Therefore, the QDA is responsible for preparing estimated queue lengths based on previous QDA estimates and current output from VIVDS. Estimates output from the QDA will be compared to ground-truth data.

Reduction of Ground-truth Data

Ground-truth data obtained from video cameras placed adjacent to the subject approach were reduced in the NCHRP 3-79 subtask for data pertaining to vehicle counts and queue length. Data were reduced by utilizing reference markers placed along the roadway during data collection. These markers were then used to calibrate video screens used in the laboratory by allowing researchers to graduate video images such that close approximations of queue length could be established. Additionally, data pertaining to vehicle counts were conducted by counting the number of vehicles that passed the stop-line during a designated 10 second interval. These data will allow the researcher to make estimates of delay in later analyses.

4. Modification of the QDA

This procedure will consist of the manipulation and modification of the QDA. The researcher intends to modify the current version of the QDA, which utilizes a queue estimate based on a weighted average of previous QDA estimates and current queue measurements from VIVDS to establish current QDA queue estimates. Updated versions of the QDA will incorporate more advanced mathematical techniques such as a Kalman Filter in order to more reasonably estimate queue length and minimize erroneous detections encountered during real-time queue estimation. During this subtask, the researcher will be responsible for implementing an advanced mathematical technique and comparing output from the QDA using this technique with output using the weighting average method previously used. Additionally, a comparison of QDA output using an advanced mathematical technique will
be compared to ground-truth data. Comparisons will be conducted using statistical procedures such as a Q-Q plot or *Chi-Square* test to compare QDA output estimates to ground-truth data. It is believed that these statistical procedures will indicate the relative accuracy of the QDA.

It is the intent of this project to implement a smoothing technique, such as a Kalman Filter, that allows from the combination of estimated queue length and measured queue length to be used such that the QDA can accurately assess the queue length at a subject approach at a given instant in time. However, it will also be the responsibility of the researcher to investigate other methods for procuring queue estimates using the QDA. If the researcher finds that the Kalman Filter is not the best technique for estimating queue length, it will be the responsibility of the researcher to investigate alternative mathematical procedures for procuring accurate queue length and delay estimates.

5. Prepare Thesis

After conducting the experimental procedure outlined in this section, the researcher will prepare a document that explains the experimental procedures performed. Recommendations will be prepared pertaining to the best mathematical technique for estimating queue length using VIVDS, as well as recommendations for future research and analysis. Each task outlined in this section will be included in the final version of the Thesis and will include detailed results and discussion. The Thesis will be prepared in accordance with Texas A&M University protocols and policies.

POTENTIAL BENEFITS OF THIS RESEARCH

The use of VIVDS has many benefits with respect to cost and maintenance of these systems over other forms of vehicle detection such as inductive loops. VIVDS is an emerging system for vehicle detection that is growing in the number of systems implemented and in the number of practical applications of these systems. This research will modify an existing algorithm used for the estimation of queue length and delay at a signalized roadway approach, such that the accuracy of this VIVDS application is improved. The improved accuracy of estimates pertaining
to these measures of effectiveness can then be used for adaptive control strategies at signalized intersections and may also provide valuable data to the traffic engineer involving the performance of a subject approach.

REFERENCES


