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Group-based approach to predictive delay model based on incremental queue accumulations for adaptive traffic control systems

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ABSTRACT

In this study, we develop a mathematical framework to estimate lane-based incremental queue accumulations with group-based variables and a predictive model of lane-based control delay. Our objective is to establish the rolling horizon approach to lane-based control delay for group-based optimization of signal timings in adaptive traffic control systems. The challenges involved in this task include identification of the most appropriate incremental queue accumulations based on group-based variables for individual lanes to the queueing formation patterns and establishment of the rolling horizon procedure for predicting the future components of lane-based incremental queue accumulations in the time windows. For lane-based estimation of incremental queue accumulations, temporal and spatial information were collected on the basis of estimated lane-based queue lengths from our previous research to estimate lane-based incremental queue accumulations. We interpret the given signal plan as group-based variables, including the start and duration of the effective green time and the cycle time. Adjustment factors are defined to identify the characteristics of the control delay in a specific cycle and to clarify the relationship between group-based variables and the temporal information of queue lengths in the proposed estimation method. We construct the rolling horizon procedure based on Kalman filters with appropriate time windows. Lane-based queue lengths at an inflection point and adjustment factors in the previous cycle are used to estimate the adjustment factors, arrival rates, and discharge rates in the next cycle, in which the predictive computation is performed in the current cycle. In the simulations sets and the case study, the proposed model is robust and accurate for estimation of lane-based control delay under a wide range of traffic conditions. Adjustment factors play a significant role in increasing the accuracy of the proposed model and in classifying queueing patterns in a specific cycle. The Kalman filters enhance the accuracy of the predictions by minimizing the error terms caused by the fluctuation in traffic flow.

1. Introduction

Traffic signals are the most effective means to control conflicting traffic flows at isolated signalized junctions. Adaptive traffic control systems (ATCS), in which signal settings are established in real time on the basis of the most up-to-date

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traffic detector information, have shown better performance than fixed-time controls in many places, despite their higher construction and operation costs. To construct adaptive traffic control logics, estimation of a control delay incurred by queued vehicles in both long-term and short-term analysis periods is required for the control system. The great part of the control delay, which is commonly used as the performance index in ATCS, was derived from Webster's theories and equations (Webster, 1958), stochastic queueing theory (Saaty, 1961), queued vehicular delay (Miller, 1963), and time-dependent delay formula (Akçelik, 1980).

The estimation methods of the control delay have been integrated with major queue estimation methods, including the conservation equation (Lindley, 1952) and the shockwave theory (Lighthill and Whitham, 1955; Richards, 1956). Following the aforementioned cornerstones for the development of a control delay and queue estimation methods, diverse delay estimation methods have been developed, including both deterministic and stochastic characteristics of a control delay. The fundamental concept of the control delay, the incremental queue accumulation (IQA), has been continuously developed in the U.S. Highway Capacity Manual (TRB, 2010) to improve the accuracy and robustness of the delay estimation methods.

Because of its simplicity, a stage-based method defined by a predetermined sequence of stages and intergreen periods is currently the most common technique used to construct signal timing plans at isolated signalized junctions and networks. Allsop (1971, 1972) constructed mathematical programs to minimize delay and maximize capacity at isolated junctions. To pursue a more flexible structure of signal timings and greater applicability to diverse urban traffic and road geometric conditions, a group-based method, in which signal settings are defined by the start and duration of green signal groups, was introduced by Heydecker and Dudgeon (1987) and Heydecker (1992). This method included a procedure to simultaneously optimize the structure of intergreen periods, a cycle length, and a signal sequence. Silcock (1997) crystallized a group-based optimization method at isolated signalized junctions to specify a detailed mathematical framework for the procedure. Wong (1996), Wong and Yang (1997) extended the group-based method for area traffic controls with derivatives of the performance index (Wong, 1995). Wong and Wong (2003a, b) and Wong et al. (2006) devised a lane-based approach to integrate a group-based optimization method with the geometric design of lane markings. The notable advantage of the group-based method is the flexibility of signal timings to optimize both signal timings and a cycle structure without the use of a predefined set of stages and a signal sequence.

For adaptive control logics, a two-phase heuristic signal control algorithm, which was one of the first contributions to real-time responsive signal control systems, was introduced by Dunne and Potts (1964) and Green (1967). The fundamental concept of real-time responsive signal control systems was specialized into traffic-actuated control and ATCS. Morris and Pak-Poy (1967) and Gordon et al. (2005) proposed traffic-actuated control systems that use simple logic to extend and terminate the current state of a signal controller on the basis of real-time traffic information collected from stop-line or upstream detectors. Despite its simplicity and relatively widespread availability in the field, these systems have several challenges, such as a rigid cycle structure, reactive logics to only current traffic conditions, an absence of optimal solutions for long-term or large-scale networks, and a lack of effectiveness in oversaturated traffic situations. To overcome these critical issues, simple responsive signal control systems have evolved into a more comprehensive and complicated form of ATCS with the concept of long-term and short-term control delay as the performance index. Miller (1963) developed an algorithm to operate a simple traffic-actuated logic according to vehicular delay as a binary choice approach, which is one of the most common concepts in the ATCS. Smith (1979a, b, 1981), Smith and Ghali (1990), Smith and Van Vuren (1993), Smith (1983), and Smith and Mounce (2015) continuously developed one of the most important theoretical philosophies of ATCS—the P0 signal control policy—over several decades. Following both Miller's algorithm and the P0 signal control policy, the store and forward modeling approach, which is the foundation of mathematical models to optimize signal timings in real time, was developed and applied in diverse traffic conditions by Gazis (1964), Gazis and Potts (1965), Grafton and Newell (1967), Ross et al. (1971), Rosdolsky (1973), D'ans and Gazis (1976), Bang and Nilsson (1976), Michalopoulos and Stephanopoulos (1977a, b), and Aboudolas et al. (2009). The methods to construct a cycle-structure according to a diverse level of temporal and spatial scales of control delay have been installed in many places such as PRODYN (Farges et al., 1983), SCOOT (Hunt et al., 1981), OPAC (Gartner, 1983), RHODES (Mirchandani and Head, 2001), ACS-Lite (Luyanda et al., 2003), and CRONOS (Boillot et al., 2006). They are based on the store and forward philosophy combined with a diverse rolling horizon predictive model for the control delay and turning movements, dynamic programming methods, and additional special features. In addition to the adaptive control approaches mentioned above, Varaiya (2013) proposed the max pressure traffic signal control policy at both isolated signalized junctions and networks. The max pressure control only requires turning flows and queue lengths at each intersection and adjacent intersections for network optimization without prior knowledge of traffic demands. To reduce the computational demands in a real-time calculation of signal timings with flexible reasonable analysis periods and good performance, Smith (2011), Ge and Zhou (2012), Han et al. (2014), and Han and Gayah (2015) consistently studied continuum signal models to approximate traffic dynamics. ATCS take full advantage of their use of sensor technologies to update traffic patterns in real time and to pursue flexibility in adjusting the control strategies to cater to these most up-to-date traffic patterns in an adaptive manner according to estimates of the control delay in real time.

To introduce a group-based method in ATCS, Lee et al. (2015a) took the first step toward estimation of lane-to-lane turning flows, which is the essential input for construction of adaptive signal control logic on a real-time basis. Lee et al. (2015b) then developed a real-time estimation method of lane-based vertical queue lengths based on discriminant models and estimated downstream arrivals to estimate cycle-delay for adaptive control logics. In this study, we devise a method with which to estimate lane-based control delay on the basis of the required temporal and spatial information to calculate real-time arrival and discharge rates in IQAs obtained from the aforementioned lane-based queue-length estimation method.