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Vehicle actuated signal performance under general traffic at an isolated intersection

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ABSTRACT

We study green extension of a two-phased vehicle actuated signal at an isolated intersection between two one-way streets. The green phase is extended by a preset time interval, referred to as critical gap, from the time of a vehicle actuation at an advance detector. The green phase switches if there is no arrival during the critical gap. We develop an exact model to study the intersection performance with traffic following Poisson processes. We further extend the model to approximate the case of general traffic. Our model in the general case works well compared with Monte Carlo simulation. A few major observations include: (1) The optimal critical gap decreases with the traffic; (2) The optimal critical gap can be much larger (up to 5 s) than the common presumption of 2–3 s; (3) Queue clearance policy is not nearly optimal in general even in the case of heavy traffic.

1. Introduction

Vehicle actuated signal systems have been widely adopted in traffic control at road intersections for their adaptability to traffic. Among the over 150,000 signalized intersections in the major 106 metropolitan areas surveyed in 2004 by the Bureau of Transportation Statistics, over 50 percent are fully or semi actuated (FHWA, 2004). This percentage indicates a stunning number of actuated intersections nation or world wide, not considering the increasing percentage of actuated intersections due to deployment of intelligent transportation systems (ITS). It is therefore significant to study control strategies at these intersections in order to alleviate the exacerbating urban traffic congestion.

A current consensus among various signal control schemes is that green time should first guarantee queue clearance at each direction. A major difference between them is in how to extend the green time after the vehicle queue has been dissipated. In this paper, we study a special scheme that controls the green extension solely based on the time interval between vehicle arrivals (referred to as headway or gap for simplicity) after queued vehicles have been discharged. In this scheme, typically an advance detector is located at a distance prior to the intersection such that an arriving vehicle triggers a green time extension in order to pass through without stop. This extended time period actuated by the vehicle is called *critical gap* in this paper. If there is no vehicle actuation during a critical gap, the green phase switches to clear queues in other approaches. In this way, the actuated system dynamically allocates the green time between multiple approaches according to vehicle arrivals. Note that the terms gap and headway are exchangeable in this paper and are both measured in time.

Clearly, the critical gap is the control variable in this special scheme. Configuration of the critical gap in such a scheme is

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important to the overall signal performance as it determines the total green duration in each approach. In addition, the green durations of approaches have a profound effect on each other. Take an intersection between two one-way streets, namely approach 1 and approach 2, as an example. A green duration of approach 1 largely determines the number of waiting vehicles accumulated in approach 2, and has impact on the immediate next green duration of approach 2. Similarly, the green duration of approach 2 impacts that of approach 1. In this way, the characteristics in both approaches interact to determine the signal evolution and intersection performance. Therefore, the critical gap in one approach, although seemingly only affects directly the green duration of its own approach, has implications to all the green phases.

In this paper, through an idealized intersection between two one-way streets, we examine the signal system performance in relation to the setup of critical gaps. The purpose of the paper is not to provide a tool for general intersection performance evaluation, but for insights into this complex control scheme through simple cases. Literature has indicated that even a reasonably sized intersection with moderate traffic is difficult to model.

Many literature and practices assume that the critical gap is exogenous, and that it is determined by the travel time from an upstream loop detector to the intersection (see, for example, Bonneson and Mccoy, 1995). This paper, instead, coincides with several pioneer works such as Darroch et al. (1964), Newell (1969), Cowan (1978), and later Viti and Van Zuylen (2010), which all take the critical gap endogenous. We will analytically examine its effect on intersection performance in this paper. The findings about critical gap will help determine the location of detectors prior to intersections.

The significance of the critical gap to the signal performance at an actuated intersection has long been recognized (for examples, Akçelik, 1981; Lin, 1982a; Courage et al., 1996). A major implication as mentioned earlier, the critical gap largely determines the dynamic interaction of phases by directly affecting the random green times. It is a challenging task to consider the interactive random phases for intersection signal performance. There are two classes of literature according to how the random phases are treated in modeling. In the first class, models represent each random phase with its expected green time duration. Some representative literature of this class includes Akçelik (1994), Lin (1982b) and Lin and Courage (1996). When the random green times are represented by their expected values, resemblance of the 'system' to the fixed timing signal gives rise to many formulas following the format of the Webster's equation (Webster, 1958) such as Kimber and Hollis (1979) and Akçelik (1994). An advantage of models in this class is its relative simplicity for modeling and (often) empirical formulas for easy application. The well-known works along this line include Akçelik and Rouphail (1993), Akçelik et al. (1997), Daniel et al. (1996), Li et al. (1994, 1996), Malakapalli and Messer (1993), and Rouphail et al. (1997). Our work falls in the second class of literature such as Darroch et al. (1964), Newell (1969), and Cowan (1978), which models phase interaction by explicitly considering each phase as a random variable. The second class of literature is rather scant, primarily because of the inherent technical challenges and rather restrictive assumptions.

Darroch et al. (1964) and Tanner (1953) appear to be the only two developing exact analytical models in settings very similar to ours. Both of them develop analytical models to this complex traffic control problem, but neither conducted numerical tests probably due to the then limited computing power. There are some other literature, as mentioned in Darroch et al. (1964), each studying a similar problem in a different but rather restrictive setting. For example, Hawkes (1963) studies the performance with zero green extension and zero time loss from switching. Lehoczky (1972) studies the bunching effect of vehicle arrivals. In the 1970s, additional research was conducted. Cowan (1978) studies bunch arrivals but assumes a vehicle headway within bunches. Cowan (1978) specially treats vehicle headway greater than a value 1.0, which is unnecessary because headway can be any nonnegative value when multiple lanes are considered in a direction. After the 1980s, there has been little analytical result on this problem except for a few examples such as Mirchandani and Ning (2007) and Viti and Van Zuylen (2010). The intersection control is a complex process. The early attempts to modeling this process are rather limited.

In this paper, we study two scenarios, Poisson processes of vehicle arrivals and general stationary arrivals of heavy traffic respectively, both of which trace back to their origins of literature as early as in the 1950s. The first scenario addresses a similar problem as in Darroch et al. (1964), but with a different modeling methodology and more extensive numerical tests. A primary contribution of this paper is made in the second scenario with stationary and heavy traffic, which has never been studied before in our best knowledge. The first scenario sets the framework for the second to build on. In the second scenario, we develop asymptotic models in general traffic taking green extension as endogenous. Our developed formulas evaluate the intersection performance well, assessed with numerical simulation, when the critical gap is present. Among the relevant literature, Newell (1969) develops approximated performance evaluation in a restrictive condition that does not allow green extension.

Organization of this paper is as follows. In Section 2, we define the problem, followed by development of analytical formulas for the expected green times, their variances as well as vehicle delay. Section 3 develops delay function in terms of green extension. Section 4 extends the study into the case of stationary and heavy traffic. We conclude this paper in Section 5.

2. Expectation and variance of green times

We start with the problem definition between two one-way streets.

2.1. Problem statement

Consider a fully actuated signal system at an isolated intersection between two one-way streets without turning vehicles, characterized by a major and a minor approaches respectively. We assume that there are only two phases, each dedicated to traffic in one approach. Each phase has a green and a red time intervals. Vehicles proceed in green and stop in red signals. Vehicle arrivals from the two approaches follow two homogeneous Poisson processes. We consider a special yet popular control scheme whose green interval