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Integrated optimization of lane markings and timings for signalized roundabouts

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A B S T R A C T

Installing signals has long been proved to be a cost-effective solution to increase capacity and treat unbalanced flows at modern roundabouts (Shawaly et al., 1991). However, signal optimization methods for conventional intersections do not directly apply to roundabouts due to the complexity of operating signals at circulatory lanes, designing special phase structure and lane marking settings, and treating left-turn movements, particularly when there are more than two lanes at approaches of a roundabout. This paper contributes to developing an integrated optimization model that is able to simultaneously determine lane markings and timings for a signalized roundabout. A precedence graph is uniquely designed to formulate a unified phase structure at both approaches and circulatory lanes. Left-turn movement queuing section at circulatory lanes is modeled as an intersection approach with short lanes and upstream signals, where queuing diagram is employed to model the capacity, queue length, and queue clearance for left turns at the second stop line. Capacity maximization, cycle length minimization, and delay minimization problems are formulated to optimize the operation of a roundabout. Real-world operational constraints are also taken into account in the optimization process to ensure feasibility and safety. Case study and sensitivity analyses results have demonstrated the effectiveness of the proposed model and provided guidelines for best application of the proposed control strategy.

1. Introduction

Roundabout has been used for more than 50 years all over the world and is becoming increasingly popular nowadays for traffic calming. It is estimated that as of April 2010, over 2000 roundabouts have been built in the United States and Canada (Pochowski, 2010), and more of that exist in cities in China. However, the bottleneck of a roundabout with two or more circulatory lanes lies in its weaving sections, where the vehicles enter or leave the roundabout (Valdez et al., 2011), and one typical disadvantage of roundabouts is its failure to handle high traffic demands due to particular characteristics of weaving areas (Akçelik, 2003). Replacing a roundabout by an ordinary signalized intersection might be a feasible alternative at this situation but usually at the risk of high construction costs and loss of safety and efficiency during nonpeak hours. Hence, transportation professionals are looking for inexpensive and convenient solutions to improve its operation, and one of the low-cost options is adding traffic signals on the roundabout.

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Previous studies on modern roundabouts focus on the capacity (Çalişkanelli et al., 2009; Hagring et al., 2003; Polus et al., 2003), delay (Al-Madani, 2003; Al-Omari et al., 2003; Hidas, 2002), geometric design, and safety (Flannery, 2001; Hydén and Varhelyi, 2000; Persaud et al., 2001; Saccomanno et al., 2008) without signal controls. Although the idea of using signals at roundabout was developed in the 1970s (Davies et al., 1980), traffic signals are mainly installed on the approaches of a roundabout in most literature and practices (Anderson and Martin, 1994; Lines, 1995; Webb, 1994). Studies show that metering signals can reduce the overall delay, queue length, emissions, and improve traffic safety (Akçelik, 2006).

However, conflicts in weaving sections of a roundabout cannot be completely eliminated by simply metering traffic at approaches. Unbalanced entry flows and conflicts between entering flows and leaving flows have not been properly addressed, resulting in long queues, delays and spillback to upstream intersections in many cases (Ozbay et al., 2008).

To deal with the above critical operational issue, we have developed a so-called Two-Stopline-for-Left-Turn (TSLT) control strategy for roundabouts to eliminate conflict points and weavings using signals installed both on entry approaches and circulatory lanes (Yang et al., 2004). However, interactions between signals at approach lanes and circulatory lanes as well as the impact of the second stop-line signals have not been accurately captured in their study. In addition, queue evolution process at circulatory lanes was not explicitly modeled, which could result in inaccuracy in calculating the capacity, clearance time, and vehicle delays.

Although many signal timing optimization methods for conventional intersections assuming lane markings as an exogenous input (Cai et al., 2009; Mirchandani and Head, 2001; Murat and Gedizlioglu, 2005; Trabia et al., 1999; Wong, 1997; Yu and Recker, 2006), the impacts of lane markings on optimal signal timings cannot be neglected. For roundabout, neglect of the impacts of lane markings may lead to unequal lane usage (Akçelik, 1997; Ma et al., 2013). Separate consideration of lane markings and signal timings may also yield sub-optimal results. In reality, it is very difficult to come up with an optimal set of lane markings for traffic signal design especially with an unbalanced flow (Wong and Heydecker, 2011; Wong and Wong, 2003), and the second stop line for left turns makes the optimization of lane markings and signal timings even more complex.

This research, proposed to remedy the aforementioned deficiencies, aims to develop an integrated optimization model to simultaneously design lane markings and signal timings at roundabout approaches and circulatory lanes. In the proposed model, a unified phase structure for signals at approaches and circulatory lanes is formulated by a precedence graph, and left-turn movement queuing section is represented by an approach with short lanes and upstream signals, where queuing diagram is employed to model the capacity, queue length, and queue clearance for left turns at the second stop line. Capacity maximization, cycle length minimization, and delay minimization problems are formulated for best operations of a roundabout. Real-world operational constraints are also taken into account in the optimization process to ensure feasibility and safety.

The remainder of the paper is organized as follows. Section 2 illustrates the control concept, phase structure representation, and notations adopted in this paper. Operational constraints of the control model are discussed in Section 3, followed by formulations of capacity maximization and delay minimization control problems in Section 4. Case studies and sensitivity analysis are performed in Section 5 to demonstrate the effectiveness of the proposed model. Section 6 concludes the study.

2. Basic control concepts

2.1. Two-Stopline-for-Left-Turn control (TSLT)

For purpose of illustration of the TSLT concept, this section employs a typical four-arm roundabout as an example (see Fig. 1). Note that the proposed control strategy is transferrable to roundabouts with more or fewer arms.

As shown in Fig. 1, TSLT control requires setting a stop line for each left-turn movement on the approach and the circulatory roadway, respectively. The basic control logic of TSLT is given by: (1) Through traffic and left-turn traffic use different lanes and are controlled by different signal heads; (2) left-turn movement stops twice at two stop lines, one located at the entering approach and the other on the opposite circulatory lanes (see P–P' and N–N' in Fig. 1a for approach 1); and (3) phase transition follows the sequence shown in Fig. 1b–d.

2.2. Notations

To facilitate the model presentation, key notations used hereafter are summarized in Table 1.

2.3. A precedence graph representation of phase diagram

Precedence graph was first proposed to formulate the ring-barrier structure in a decision model for priority control and was validated as an effective method to model and evaluate alternative timing schedules (Head et al., 2006). Fig. 1a shows the basic phase structure of a signalized roundabout. Compared with typical North American dual-ring, 8-phase controller, their differences lie in: (1) there are no barriers between phases and (2) there are two left turn permitted phases in each ring. Besides, the lengths of phase 2, phase 5, phase 8, and phase 11 are related to the lengths of phase 3, phase 6, phase 9, and phase 12 (see Fig. 1a) depending on the available space between first and the second stop lines.