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Identification and optimization of traffic bottleneck with signal timing

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Abstract: In urban transportation network, traffic congestion is likely to occur at traffic bottlenecks. The signal timing at intersections together with static properties of left-turn and straight-through lanes of roads are two significant factors causing traffic bottlenecks. A discrete-time model of traffic bottleneck is hence developed to analyze these two factors, and a bottleneck indicator is introduced to estimate the comprehensive bottleneck degree of individual road in regional transportation networks universally, the identification approaches are presented to identify traffic bottlenecks, bottleneck-free roads, and bottleneck-prone roads. Based on above work, the optimization method applies ant colony algorithm with effective green time as decision variables to find out an optimal coordinated signal timing plan for a regional network. In addition, a real experimental transportation network is chosen to verify the validation of bottleneck identification. The bottleneck identification approaches can explain the features of occurrence and dissipation of traffic congestion in a certain extent, and the bottleneck optimization method provides a new way to coordinate signal timing at intersections to mitigate traffic congestion.

Key words: traffic bottleneck; bottleneck indicator; signal timing coordination; ant colony algorithm; discrete-time model

1 Introduction

In urban transportation network, traffic congestion is likely to occur at some locations, which are called traffic bottlenecks (Wright and Roberg 1998), and that may account for 40% of significant factors causing traffic congestion (US Department of Transportation 2006).

Some fixed static bottlenecks are well known, such as the poor road alignment, the road width narrowing, on-ramps, off-ramps, and even some of network topologies (Sun et al. 2014). Bottlenecks can affect the road capacity (Chung et al. 2007; Guumlnther et al. 2012; Tang et al. 2012). Some control strategies were given for traffic bottlenecks, such as balancing vehicular traffic (Siebela et al.

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2009), preventing wide moving jams from propagating continuously upstream according to three-phase traffic theory (Kerner 2005, 2008), mitigating freeway traffic congestion by reinforcement of learning ramp metering (RLRM) control method (Wang et al. 2012), and introducing traffic signal to control traffic flows and improve bottleneck capacity (Lo and Chow 2004; Zhao and Gao 2006; Li et al. 2007; Li et al. 2013).

However, some bottlenecks and their influences are relatively obscure and they need further analysis. Leclercq (2007) proposed an extension of LWR model to describe the effect of road section reductions and the influence of slow-moving vehicles (such as buses) representing as moving bottlenecks, so that traffic operation strategies could be evaluated. Juran et al. (2009) developed a dynamic traffic assignment model to evaluate the effects of moving bottlenecks on network performance, which defined a situation that a slow-moving vehicle disrupted the continuous flow of general traffic. Coifman and Kim (2011) noted that freeway bottlenecks appeared to occur over an extended distance and developed a theory to explain the underlying mechanism. Gentile et al. (2007) took road entry and road exit capacities as time-varying bottlenecks to represent the formation, dispersion, and propagation of vehicle queues on road links. Zheng et al. (2011) located active bottlenecks by wavelet-based energy using loop detector data from a freeway, and analyzed important features of bottleneck activations in congested traffic systematically. Kerner (2011) presented a network breakdown minimization principle to minimize probability of congestion occurrence in the whole network, which was much more applicable for real traffic networks that were far from equilibrium and stationary compared with Wardrop's principles. Robin and Vincent (2012) found the bottleneck queuing congestion was due to the toll schemes, because drivers would slow down or stop just before reaching a toll station and wait until the toll is lowered from one step to the next step, so an optimal tolling scheme should be proposed to prevent or limit drivers' braking. Yao et al. (2010) gave the financial derivatives for congestion in a decision environment with active bottlenecks, which could reduce total social cost by altering drivers' departure behavior and reducing drivers' risks of high variance of trip costs. Zhang and Levinson (2010) proposed a methodology to systematically identify active freeway bottlenecks in a metropolitan area. It is found that ramp metering can increase the bottleneck capacity by postponing and sometimes eliminating bottleneck activations, accommodating higher flows during the pre-queue transition period, and increasing queue discharge flow rates after breakdown.

Besides the above-mentioned bottlenecks, roads under certain circumstances frequently act as traffic bottleneck. With the traffic volume increasing, some roads have blocked and others not, some are prone to congesting while others not. It is obvious that bottlenecks are related with signal timing and traffic flow volume. Hence, it will be very helpful to find an approach to identify such traffic bottlenecks and find optimization approaches to coordinate signal timing at intersections. In fact, there are various optimization approaches with diverse motives, such as network decomposition (Lieberman and Chang 2005), managing oversaturation traffic flows (Hu et al. 2011), minimum delay and better traffic fluency between adjacent intersections (Chin et al. 2011), dissipation of queues and removal of blockages (Putha et al. 2012), and adjustment of road capacity (Ma et al. 2013).

There are two contributions of this work. One is to propose approaches of identifying traffic bottle roads, bottleneck-prone roads in urban transportation network with two factors, signal timing at intersections and properties of left-turn lanes and straight-through lanes of roads. The other is to propose an approach to reduce impacts of traffic congestion arising from traffic bottlenecks by signal timing at intersections in a regional network.

2 Model formulation

2.1 Research objective

An urban transportation network is described as

$$UTN = \{I, R\}$$

where $I = \{I_s, s = 1, \cdots, S\}$ is the set which gathers the S signalized intersections in the network; $R = \{R_m, m = 1, \cdots, M\}$ is the set which gathers the M roads in