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A capacity maximization scheme for intersection management with automated vehicles

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Abstract

With the advent of connected and automated vehicle technology, in this paper, we propose an innovative intersection operation scheme named as MCross: Maximum Capacity inteRsection Operation Scheme with Signals. This new scheme maximizes intersection capacity by utilizing all lanes of a road simultaneously. Lane assignment and green durations are dynamically optimized by solving a multi-objective mixed-integer non-linear programming problem. The demand conditions under which full capacity can be achieved in MCross is derived analytically. Numerical examples show that MCross can almost double the intersection capacity (increase by as high as 99.51% in comparison to that in conventional signal operation scheme).

Keywords: Intersection capacity; dynamic lane assignment; signal operation; connected vehicles; automated vehicles

1. Introduction

Intersections are frequent bottlenecks of an urban road network, with limited capacity that may cause residual queues and excessive congestion. To improve the utilization of the intersection capacity, some conventional mitigation strategies, such as throughput maximization, queue balancing, negative offset, metering and gating, have been proposed and utilized to reduce congestion to certain extent (e.g. Gazis, 1964; Lieberman et al., 2000; Liu and

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Chang, 2011; Sun et al., 2015a, 2016). However, further improvement of intersection efficiency by merely adjusting signal control parameters under conventional intersection operation scheme is very difficult. The inefficiency of current intersections is not merely because their capacity is under-utilized, but, more importantly, because the capacity itself is not maximized but constrained by conventional intersection management scheme.

At a conventional intersection, capacity can be calculated for a lane or a lane group under given roadway, geometric, traffic, and control conditions (HCM, 2010). Considering the capacity of an intersection, it should be the summation of capacity for all lane groups (Coates et al., 2012). If more lane groups can be served simultaneously, the intersection capacity would be greater. To increase intersection capacity, researchers have proposed several unconventional intersection designs or traffic operation schemes. To date, there are mainly two types of unconventional intersection designs that potentially increase intersection capacity by simultaneously utilizing all approaching lanes of a road. The first type is represented by the continuous flow intersection (CFI) (Goldblatt et al., 1994), which employs displaced left-turn lanes to eliminate the conflict between left-turn traffic and opposing through traffic at an intersection so that both movements can pass the intersection simultaneously in one signal phase (Fig. 1(a)). Other similar designs include parallel flow intersection (PFI) (Parsons, 2007) and CFI-Lite (Sun et al., 2015b). The second type is the tandem intersection (TI), which arranges left-turn vehicles and through vehicles in tandem queues on approaching lanes so that each movement can use all lanes during its green time (Fig. 1 (b)) (Xuan et al., 2011). However, for CFI or TI, capacity can be fully utilized only if the demand matches well with the geometry regarding the number of lanes for each movement and the location of pre-signals. Zhao et al. (2015) presented an integrated optimization of lane markings, the length of the displaced left-turn lane and the signal timings to further improve the efficiency of CFI and PFI. However, their method is applicable only when the traffic demand is stable. Due to cycle-by-cycle fluctuations in traffic volumes of different movements, the intersection capacity with these unconventional designs, albeit usually being increased significantly, can be hardly tapped to its fullest.

The advent of connected and automated vehicle (CAV) technology provides promising opportunities to improve intersection operation with additional degree of freedom. Towards this end, numerous research has been proposed aiming at optimizing vehicles' trajectories based on signal status information (Guler et al., 2014; Rakha and Kamalanathsharma, 2011; He et al., 2015; Wu et al., 2015), optimizing signal operation based on approaching vehicles' trajectories (Goodall et al., 2013; He et al., 2014; Feng et al., 2015), as well as jointly optimizing both signal operation and vehicle trajectory (Li et al., 2014). Reduction of vehicle delay, number of stops, fuel consumption and emissions were reported from their studies. Assuming a 100% CAV environment, several

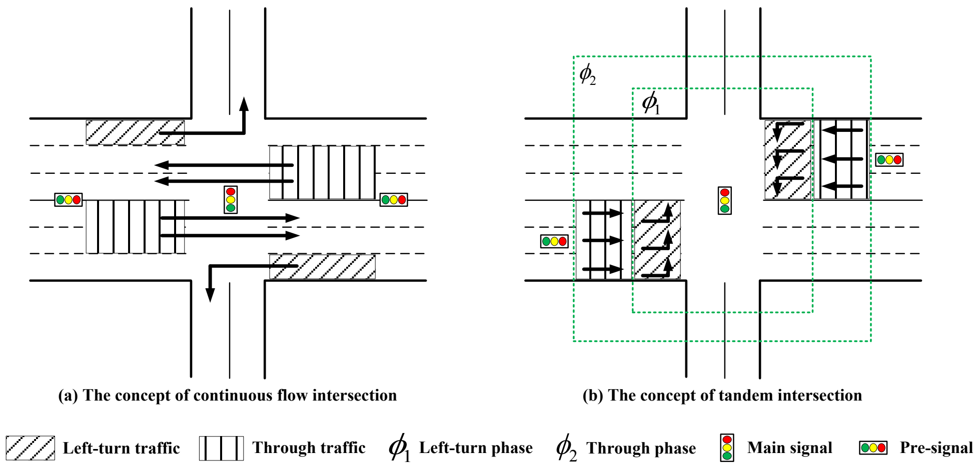

Fig. 1. Unconventional intersection designs that increase capacity: (a) continuous flow intersection; (b) tandem intersection.

signal-free intersection management strategies were also proposed based on reservation-based conflict avoidance algorithms (Dresner and Stone, 2008; Fajardo et al., 2011; Lee and Park, 2012; Zohdy and Rakha, 2014). These