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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 are 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).

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 to reduce congestion to certain extent (e.g. Gazis, 1964; Lieberman et al., 2000; Liu and Chang, 2011; Sun et al., 2015a, 2016). However, further improvement of intersection efficiency by merely adjusting signal control parameters is very difficult under conventional intersection operation scheme. The inefficiency of current intersections is not merely because their capacity is under-utilized, but, more importantly, because the capacity is not maximized but rather 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). Capacity of an intersection is typically the summation of capacity for all lane groups (Coates et al., 2012). If more lane groups can be served simultaneously, the intersection capacity would increase. To do such, researchers have proposed several unconventional intersection designs or traffic operation schemes. So far, there are mainly two types of unconventional intersection designs that would 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

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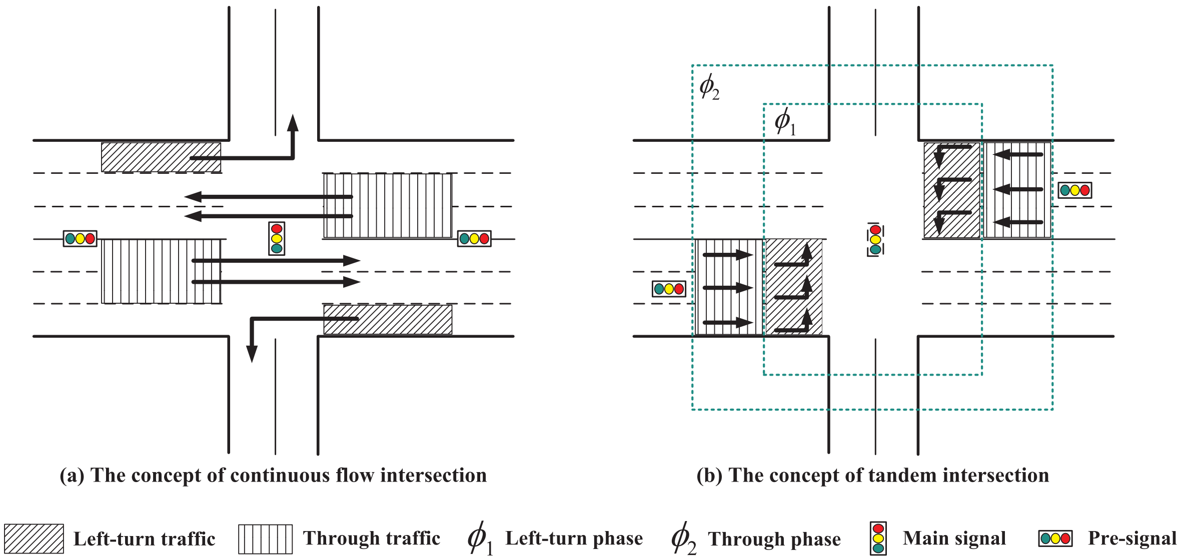

Fig. 1. Unconventional intersection designs that increase capacity: (a) continuous flow intersection; (b) tandem intersection.

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, is 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 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 strategies, however, mainly focused on longitudinal vehicle control with conventional intersection management. Other than achieving shorter inter-vehicle headways from CAVs (e.g., Talebpour and Mahmassani, 2016), they did not demonstrate evidence of improvement for intersection capacity. A most recent research showed that, in some cases, such reservation-based intersection control methods can cause larger delay and disrupt platoon progression, and therefore are less efficient than conventional traffic signals (Levin et al., 2016). On the other hand, with connectivity and automation of the CAVs, more versatile traffic management strategies become viable by deploying both longitudinal and lateral control, e.g. cooperative lane changing and car following. Thereby, vehicles can be dynamically assigned to different lanes when arriving at the intersection, and virtual CFI or TI can be developed for advanced traffic operation scheme with CAVs. To the best of our knowledge, this type of concept has not yet been introduced.

In this paper, we propose an innovative intersection operation scheme for CAVs. This new scheme inherits the concepts of unconventional intersection design, i.e. CFI or TI, to use all lanes of a road at any time, and benefits from the maneuverability of CAVs to determine the lane assignment dynamically. By doing this, the proposed method can maximize the capacity of intersections with various traffic demand.

2. MCross: maximum capacity intersection operation scheme for CAVs

The traffic signal operation scheme proposed in this paper is named as MCross: Maximum Capacity inteRsection Operation Scheme with Signals. The concept of MCross is shown in Fig. 2, in conjunction with the conventional signal operation scheme for comparison. In a conventional operation scheme (Fig. 2(a)), each leg connected to the intersection is divided into two directed (ingress and egress) roadways by a median barrier (the centerline), and then each ingress roadway is further divided into through and left-turn lanes by lane markers. For simplicity, right-turn traffic is not considered in this paper. The signal phases are illustrated by a series of intersection-centered squares in dashed lines. Vehicles in the innermost square can pass the intersection within current phase if they have the right-of-way, and vehicles in any ring between two squares can pass the intersection in the subject phase if not blocked by queues. Conventionally, four phases in a cycle are required to serve through and left-turn movements from all legs. For example, the first phase (Φ_1 in Fig. 2(a)) is used to serve eastbound (EB) left-turn and westbound (WB) left-turn movements, leaving the capacity of any other approaching lane unused.

In MCross, with all vehicles being CAVs, the capacity of an intersection can be maximized with the following two steps. First, the