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A continuous-flow-intersection-lite design and traffic control for oversaturated bottleneck intersections

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ABSTRACT

Oversaturation has become a severe problem for urban intersections, especially the bottleneck intersections that cause queue spillover and network gridlock. Further improvement of oversaturated arterial traffic using traditional mitigation strategies, which aim to improve intersection capacity by merely adjusting signal control parameters, becomes challenging since exiting strategies may (or already) have reached their "theoretical" limits of optimum. Under such circumstance, several novel unconventional intersection designs, including the well-recognized continuous flow intersection (CFI) design, are originated to improve the capacity at bottleneck intersections. However, the requirement of installing extra sub-intersections in a CFI design would increase vehicular stops and, more critically, is unacceptable in tight urban areas with closed spaced intersections. To address these issues, this research proposes a simplified continuous flow intersection (called CFI-Lite) design that is ideal for arterials with short links. It benefits from the CFI concept to enable simultaneous move of left-turn and through traffic at bottleneck intersections, but does not need installation of sub-intersections. Instead, the upstream intersection is utilized to allocate left-turn traffic to the displaced left-turn lane. It is found that the CFI-Lite design performs superiorly to the conventional design and regular CFI design in terms of bottleneck capacity. Pareto capacity improvement for every traffic stream in an arterial system can be achieved under effortless conditions. Case study using data collected at Foothill Blvd in Los Angeles, CA, shows that the new design is beneficial in more than 90% of the 408 studied cycles. The testing also shows that the average improvements of green bandwidths for the synchronized phases are significant.

1. Introduction

With traffic congestion continuing to grow in urban areas around the world, more and more signalized intersections are operated under oversaturated conditions. Under the condition of oversaturation, typical traffic control strategies do not work as efficiently as necessary. As indicated by the 2011 Traffic Signal Operation Self Assessment surveys (NTOC, 2011), the majority of agencies involved traffic signal operation and maintenance are already stretched thin and challenged to provide adequate service to drivers in their jurisdictions. Oversaturated conditions present an additional burden for practitioners that do not have adequate tools for addressing such situations (NCHRP, 2012).

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Numerous efforts have been made to address oversaturation. Over the years, researchers have realized that the onset of oversaturation is usually caused by vehicle queues first occurring at some bottleneck intersections (i.e. critical intersections) and then propagating upstream and sprawling all over the arterial network, causing so-called network gridlock (Gazis, 1964; Abu-Lebdeh and Benekohal, 2000; Daganzo, 2007; Wu et al., 2010). Therefore, an efficient way to mitigate oversaturation is to improve the utilization of the capacity at bottleneck intersections in order to prevent queue sprawling and hasten recovery after oversaturation. Aligning with this concept, some classical mitigation strategies, such as throughput maximization, queue balancing, negative offset, and metering and gating, have been proposed for many years and have successfully relieved arterial congestion at some level (e.g. Gazis, 1964; Michalopoulos and Stephanopoulos, 1977a,b; Chang and Lin, 2000; Park et al., 2000; Abu-Lebdeh and Benekohal, 2000; Lieberman et al., 2000; Liu and Chang, 2011; Hu et al., 2013).

However, with traffic continuing to grow significantly, further improvement of arterial traffic using traditional mitigation strategies has become challenging; simply because these strategies, which improve intersection capacity utilization by merely adjusting signal control parameters, could (or already) have reached their "theoretical" limits. As signal control essentially is an optimization problem, there must be a (or several) theoretical optimal solution(s), which, once reached, cannot be improved anymore. To address this issue, instead of purely adjusting signal timing, more and more researchers begin to seek some novel intersection geometric designs, which can be used to further resolve the problem of urban traffic congestion.

Several novel geometry designs (i.e. unconventional intersection designs) have been proposed recently to improve the capacity utilization at bottleneck intersections. Most of these designs are originated to remove the conflict between left-turn and opposite through movements since left-turn movement is one of the main causes which contribute to the inefficiency of conventional at-grade intersections. For example, some designs, such as median U-turn, simply eliminate left turns by requiring drivers to first travel straight through the main intersection and then execute their left turns by making U-turns at downstream (El Esawey and Sayed, 2013). This design reduces the total number of phases therefore increasing the intersection capacity. The drawbacks, however, are that vehicles in some traffic stream are rerouted to experience long travel distance, which not only wastes more time and fuel, but also increases the demand for the intersection (Autey et al., 2013). Other designs, such as tandem intersection design, reorganize the left-turn and through traffic in tandem before the intersection, so that all travel lanes are utilized for both left-turn and through traffic (Xuan et al., 2011). Nevertheless, lane blocking may happen if the anterior movement in tandem is somehow unable to be fully discharged.

One of the well-recognized unconventional intersection designs is the continuous flow intersection (CFI), which moves the left-turn and through movements simultaneously by adjusting the locations of left-turn or through lanes (Goldblatt et al., 1994). In a CFI design, the green time initially allocated to the left-turn and through phases can be summed up together to serve all traffic therefore significantly improving intersection capacity. The CFI design was reported to outperform other unconventional designs (Reid and Hummer, 2001; Jagannathan and Bared, 2005; El Esawey and Sayed, 2007; Hughes et al., 2010; Autey et al., 2013; Wu et al., 2014), However, the CFI design requires installation of new sub-intersections, which may generate more vehicular stops (Yang et al., 2013). It was also found that to some extent, the bottleneck for left-turn movement shifts from the main intersection to sub-intersections (Carroll and Lahusen, 2013). Moreover, the construction of sub-intersections is costly, not only in terms of money, but also the large space required (Hughes et al., 2010). Typically, sub-intersections in a CFI design are suggested to be installed 300$\sim$400 feet upstream the intersection (Bared, 2009; Hummer and Reid, 2000), while the link length between adjacent intersections along an arterial in an urban city are usually around 1000 feet. Considering the short link lengths between adjacent intersections in tight urban areas, constructing a CFI becomes almost impossible.

To conquer the aforementioned problems, this research proposes a simplified continuous flow intersections design, called CFI-Lite, to improve the capacity at oversaturated bottleneck intersections. The new design uses the existing upstream intersection, instead of newly constructed sub-intersection, to allocate left-turn traffic to displaced left-turn (DLT) lane. Thus left-turn traffic turns left (to the DLT lane) in advance at the upstream intersection. The CFI-Lite design benefits from the CFI concept to enable simultaneous move of left-turn and through traffic at the bottleneck intersection, but does not need the installation of extra pre-signal and construction of sub-intersections. Therefore, CFI-Lite is ideal for tight urban areas where the link lengths between adjacent intersections are too short to construct regular CFIs. It is obvious that problems generated from sub-intersections do not exist anymore. In addition, this research further seeks for a Pareto capacity improvement for a CFI-Lite design. A multi-objective mixed integer programming problem is formulated and, by solving this problem, the systematically improvement of the capacity of bottleneck intersections can be achieved.

The rest of the paper is organized as follows. Section 2 describes the design concept of CFI-Lite design. The comparative analysis of capacity for the conventional design, the regular CFI design and the CFI-Lite design is conducted in Section 3. Section 4 formulates the traffic control problem at CFI-Lite intersections as a multi-objective mixed integer programming problem and seeks for Pareto improvement. Section 5 briefly introduces how the CFI-Lite design is expanded to address consecutive bottlenecks. A case study using the data collected from Foothill Blvd in the city of Los Angeles, CA is shown in Section 6. Section 7 concludes the paper.

2. Design concept

Fig. 1 presents the design concept of the CFI-Lite intersections. The objective of the CFI-Lite design is to remove the conflicts between heavy left-turn movements and opposing through movements at the bottleneck intersection along an arterial.