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Optimal operation of displaced left-turn intersections: A lane-based approach

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ABSTRACT

Displaced left-turn (DLT) intersections that resolve the conflict between left-turn and opposing-through movements at the pre-signal are probably the most extensively used innovative intersection designs. The DLT intersection concept can be extended to ten different types according to the location of the left-turn transition area, the number of DLT approaches, and the possible setting of the bypass right-turn lane. This paper presents a generalized lane-based optimization model for the integrated design of DLT intersection types, lane markings, the length of the displaced left-turn lane, and the signal timings. The optimization is formulated as a mixed-integer non-linear program. This program is further transformed to a series of mixed-integer linear programming problems that can be solved by the standard branch-and-bound technique. Results from extensive numerical analyses reveal the effectiveness of the proposed method, as well as the promising property of assisting transportation professionals in the proper selection of DLT intersection types, and the design of geometric layout and signal timings.
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1. Introduction

Congestion at intersections continues to worsen in numerous cities throughout the world. This problem was conventionally treated by signal control, which included two general approaches: one was the stage-based method (Allsop, 1971; Webster, 1958) and the other was the group-based method (Heydecker and Dudgeon, 1987; Improta and Cantarella, 1984; Silcock, 1997). However, while demands on the transportation system continue to grow, the conventional treatment of intersections through the provision of left-turn bays with protected left-turn phases may not be sufficient to avoid long delays. Under oversaturated traffic conditions, signal timings are mainly adjusted to alleviate the detrimental impacts caused by oversaturation (Hu et al., 2013; Wu et al., 2010). Consequently, many researchers are considering various innovative intersection designs in their effort to enhance the intersection capacity. These treatments include the median U-turn intersection, jug-handle, superstreet intersection, paired intersection, quadrant roadway, bowties, displaced left-turn intersec-

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tion, tandem intersection, exit-lanes for left-turn intersection, and others (Goldblatt et al., 1994; Hummer, 1998a,b; Ma et al., 2013; Xuan et al., 2011; Yan et al., 2014; Zhao et al., 2015, 2013).

Among these innovative intersection designs, the displaced left-turn (DLT) intersection is rapidly becoming prevalent worldwide (Jagannathan and Bared, 2005). The main benefit of a DLT intersection is the elimination of the conflict between the left-turn and opposing-through traffic by relocating the left-turn bay a significant distance upstream (or downstream) of the primary intersection so that the left-turn flow and the through movement (or the through movement at the adjacent leg) can progress concurrently (Yang et al., 2013), thereby increasing the intersection capacity.

In the development of the displaced left-turn (DLT) intersection, several studies have demonstrated the benefits of the DLT design over other signalized intersection designs in terms of increased capacity, decreased delay and travel time, efficiency of land use, and promoted safety (Cheong et al., 2008; Dhatrak et al., 2010; El Esawey and Sayed, 2007; Inman, 2009). In order to produce the best operational strategy for the DLT intersection, extensive research has been devoted to their geometries and signal control optimization.

For convenience of application, many guidelines for the geometric design were first developed. These included the number of DLT approaches (UDOT, 2013), the distance between the crossover and the intersection (Tanwanichkul et al., 2011; WSA, 2008), the lane width of the displaced left-turn lane, the radii of the crossover movements and the left-turn movement at the main intersection (Jagannathan and Bared, 2004), and the angle between the DLT intersection left-turn lanes and the main through lanes (Hildebrand, 2007).

The geometric feature allows the primary intersection to operate with fewer traffic signal phases and conflict points than those found in a conventional intersection design (Hughes et al., 2010). However, the operation process of the DLT is complex: the left-turns should pass three stop lines and the through movements should pass two stop lines. Therefore, commercial signal timing packages may not be readily utilized to develop optimal signal timings. In the work by Jagannathan and Bared (2004), the DLT intersection was broken into a group of hypothetical intersections, and the WINQSB operational research solver was utilized to solve an optimization model for the signal timing and offsets. The model is proposed for determining delay minimization. You et al. (2013) proposed a model for a full continuous flow intersection (CFI), which is a type of the DLT intersection, with the objective of cycle length minimization to obtain signal timings based on the analysis and formulation of the queue length. Suh and Hunter (2014) further proposed two optimization approaches for the DLT intersection. One is a Monte Carlo simulation method to minimize intersection delay. The other is a bandwidth maximization method. Results showed that although the optimal bandwidth solution does not necessarily correspond to the minimum delay solution, there is a significant family of timing plan solutions with similar performance characteristics, either using the delay or the bandwidth approach. Sun et al. (2015) proposed a simplified continuous flow intersection (called CFI-Lite) design, which uses the existing upstream intersection, instead of newly constructed sub-intersection, to allocate left-turn traffic to DLT lane. Left-turn traffic turns to the DLT lane in advance at the upstream intersection. Therefore, CFI-Lite is ideal for arterials with closely spaced intersections.

Although much has been known regarding the technologies of the DLT intersection, the conventional optimization procedure is based on trial-and-error (El Esawey and Sayed, 2013), whereby an initial set of DLT intersection types is first assumed, the layout including lane markings is determined, and the signal timing is then calculated. After evaluating the performance of the intersection, the engineer may revise the design based on his/her experience until the performance of the intersection is satisfactory. However, this may not always produce the optimal design result, because it is exceedingly arduous to come up with an optimal set of DLT intersection types and geometric layouts for traffic signal design. Carroll and Lahusen (2013) pointed out that the DLT intersection creates a unique space–time relationship but has not yet been adequately addressed in the current literature. A deterministic model was proposed in that research to optimize the key design variables with the consideration of signal timing. In this way, the model could provide more accurate and time effective determination of the optimal design for the length of the displaced left-turn lane. Therefore, it is indispensable to combine the design of the layout and signal timing for the DLT.

The idea of an integrated design for isolated intersections is not new. Lam et al. (1997) attempted to combine the design of lane markings and signal timings and pointed out its potential benefits in improving intersection performance. Recently, the lane-based optimization methods for isolated intersections have been developed (Lee et al., 2015; Wong and Wong, 2003a,b; Wong and Heydecker, 2011). The design approach was termed as the lane-based method, since all key design variables were defined on a lane-basis. This makes it easier to express the set of constraints as linear equations, thus ensuring the feasibility of the solution algorithm for the optimization model.

In this paper, a systematic approach is proposed to achieve the best operational performance of an emerging design – the DLT intersection. A lane-based optimization model that combines the type of DLT intersection selection, lane markings, the length of the displaced left-turn lane, and signal timings is presented. The optimization problem is formulated as a multi-objective mixed-integer non-linear programming problem that is solved by transforming it into a series of mixed-integer linear programming models. The latter can be solved by the standard branch-and-bound technique. Results from extensive numerical analyses show that the DLT intersections outperform the conventional design in terms of improving the intersection capacity. The average and highest improvement obtained in the numerical experiment are 48.7% and 79.5%, respectively. However, the optimal designs (the type of DLT intersection selection) and the performance improvement varies significantly under different geometric configurations and traffic demand patterns.

The rest of this paper is organized as follows. In Section 2, the extension of the DLT concept is discussed. The integrated optimization model for the geometric layout and signal timing is formulated in Section 3. Evaluation of the proposed model

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