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Integrated signal optimization and non-traditional lane assignment for urban freeway off-ramp congestion mitigation

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ABSTRACT

Exiting flow from urban freeway off-ramps coupled with limited capacity and traffic weaving at the downstream intersections creates major bottlenecks in urban road network. This paper presents an integrated design model for non-traditional lane assignment and signal optimization at the off-ramp, its downstream intersection, and their connecting segment with the objective to mitigate or eliminate traffic weaving and to maximize the section's overall capacity. A mixed-integer non-linear program model is formulated to capture real-world operational constraints regarding the non-traditional lane assignment, special phasing treatment and signal timing. The mathematical model is linearized and solved by the standard branch-and-bound technique. Extensive numerical analysis and case study results validate the effectiveness of the proposed integrated model and demonstrate its promising application at locations where the upstream freeway off-ramp is located at the middle of the road cross section and the space between the stop line and off-ramp is limited.

1. Introduction

Traffic on urban freeway off-ramps often experiences difficulty in exiting due to its competition with traffic from surface streets. Using Fig. 1 as an example, when the space between the off-ramp and the downstream intersection is limited, queue at the downstream intersection during the red phase may easily prevent the off-ramp exiting traffic from merging into their target approach lanes. The resulting queue on the off-ramp then generates a spillover onto the mainstream of the urban freeways, resulting in freeway mobility loss and traffic safety problems (Cassidy et al., 2002; Cheu et al., 1998; Daganzo et al., 1999; Jin et al., 2002; Newell, 1999). On the other hand, poor utilization of the downstream intersection capacity may occur due to the fact that insufficient weaving space between freeway and surface street traffic induces extra delays and prevents vehicles from reaching the downstream stop line during the green time (TRB, 2010). Due to the aforementioned problems, off-ramps, the downstream signalized intersections, and their connecting segments often constitute the major bottlenecks in the urban road network.

To mitigate traffic congestion at those bottlenecks, transportation researchers have been investigating and implementing a variety of strategies. In review of literature, these strategies mainly fall into the following two categories: demand or access management strategies and traffic management strategies (Munoz and Daganzo, 2002; Rudjanakanoknad, 2012; Spiliopoulou et al., 2014).

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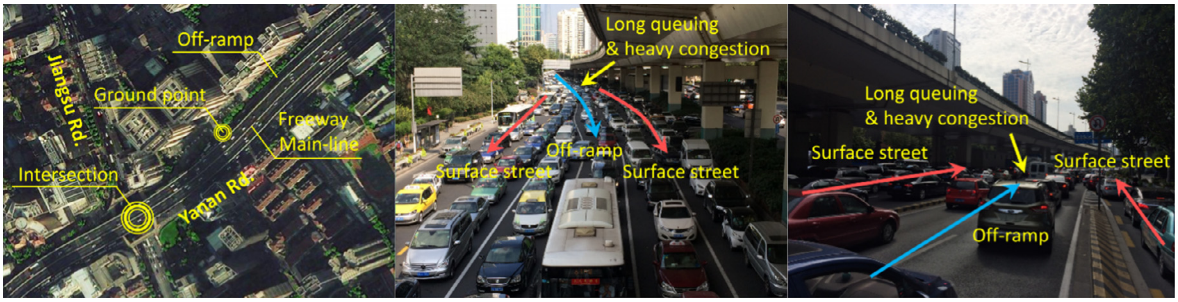

(a) Aerial view (b) View from the intersection (c) View from the end of the off-ramp

Fig. 1. Example of the complex operation condition in real world (Jiangsu Rd. and Yanan Rd. in Shanghai, China).

Demand or access management strategies improve the performance of the off-ramp areas by denying access to the preferred off-ramp once the off-ramp queue has emerged onto the freeway, or by guiding traffic to upstream ramps by variable message signs (Daganzo et al., 2002). The system optimum dynamic traffic assignment is studied at a network level (Muñoza and Laval, 2006). Since it may represent a high penalty for detoured vehicles, especially when the nearby off-ramps are far away, application of such strategies may be limited only to the special events such as those associated with large sporting events and emergency conditions such as evacuation (Liu et al., 2011, 2013). In addition, traffic demand of the freeway could also be reduced by pricing (Shen and Zhang, 2009). Although there are equity issues, it may be considered on major bottlenecks in big cities. Moreover, the road pricing strategies could be flexibly combined with other management methods (Sheu and Yang, 2008; Zhong et al., 2014).

Traffic demand diversion strategies in surface streets have also been adopted to reduce off-ramp traffic demand by detouring a certain fraction of the side road flow through underutilized and nearby parallel roads (Günther et al., 2012). There are two alternatives: detouring the flow on the side road to the local network and detouring the flow on the cross street to the local network. The former could eliminate the weaving movement upstream of the intersection, while the latter could reduce the degree of saturation of the intersection. However, these strategies would certainly cause extra driving distances and may shift traffic congestion to somewhere else in the network.

Different from demand or access management strategies, traffic management strategies mitigate off-ramp and adjacent intersection congestion by enhancing their capacities or utilization of capacities. For examples, reassigning lane usage at the freeway diverge gore area is used to mitigate the congestion caused by the insufficiency of the off-ramp capacity (Daganzo et al., 2002; Hagen et al., 2006).

At the surface street side, off-ramp congestion is mostly caused by traffic weaving or insufficient capacity of the downstream intersections (Denney et al., 2009; Lu et al., 2010; Tian et al., 2007). A number of models have been proposed to optimize the signal timing of the downstream intersection. In these models, queue detectors are installed at the upstream end of the off-ramp to prevent queue spillback onto the freeway. However, if the objective only focuses on managing traffic operation from the perspective of optimizing freeway traffic flow, the normal signal operations on the surface street will be disrupted significantly (Tian et al., 2002). In view of such deficiencies, integrated signal control models and strategies have been developed with the objective to minimize the total delay for off-ramps and their connected surface streets (Li et al., 2009; Lim et al., 2011; Mirchandani and Head, 2001; Tian and Wu, 2012; Yang et al., 2014). These signal timing strategies are useful to relieve congestion due to the fluctuation of freeway traffic and stochastic arrival pattern at the off-ramp. However, when the downstream intersection is oversaturated due to high traffic demand, lane markings of the intersection should be reorganized to further improve the intersection capacity (Hagen et al., 2006). To this regard, researchers have found that the use of dual right-turn lanes may facilitate weaving for right-turning vehicles from the off-ramp and increase the capacity of the intersection in proximity to off-ramps which are characterized by higher turning volumes (Chen et al., 2014; Yi et al., 2012). However, in most of previous studies optimizing intersection channelization to reduce traffic weaving between freeway and surface street is neglected and reorganization of the weaving segment between the intersection and off-ramp has not been considered. Additionally, very limited efforts have been made for integrated geometric layout and signal timing optimization for the off-ramp and its proximity surface street section.

In this paper, we develop an integrated design model for non-traditional lane assignment and signal optimization at the off-ramp, its downstream intersection, and their connecting segment with the objective to mitigate or eliminate traffic weaving and to maximize the section's overall capacity. Please note there are several types of ramp-street connection designs, such as the off-ramp connecting with a surface street, directly connecting with the intersection, and connecting with a local arterial with multiple adjacent intersections (Yang et al., 2015). The method proposed in this paper is mainly used on the condition that the off-ramp is connected with a surface street with an intersection at the downstream.

The idea of an integrated design is not new. Lam et al. (1997) combines the design of lane markings and signal timings and pointed out its potential benefits in improving intersection performance. To optimize these design variables in a unified framework, the lane-based optimization method was developed (Wong and Wong, 2002, 2003b). The modelling method defines all key design variables on a lane-basis. This makes it easier to express the set of constraints as linear equations, thus