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Integration of adaptive signal control and freeway off-ramp priority control for commuting corridors

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ABSTRACT

Congestion at the downstream of an off-ramp often propagates the traffic queue to the freeway mainline, and thus reduces the freeway capacity at the interchange area. To prevent such potential queue spillover and improve traffic control efficiency over the entire corridor, this study develops an integrated control system which includes three primary functions: off-ramp queue estimation, arterial adaptive signal operations, and freeway off-ramp priority control. Using detected flow data, the system firstly estimates the queue length on the target off-ramp. If no potential queue spillover is predicted, the adaptive signal control function will then adjust the intersection signal timings and provide dynamic signal progression to critical path-flows. Otherwise, the off-ramp priority control function will be activated to clear the queuing vehicles at the off-ramp. To evaluate the effectiveness of the proposed system, this study has conducted numerical studies on a freeway interchange using a well-calibrated simulation platform. The experimental results reveal that the overall network performance can indeed be improved under the proposed control system, compared with other operational strategies. Further analyses of freeway time-dependent travel time distribution also evidence the effectiveness of the proposed system in preventing off-ramp queue spillover.

1. Introduction

Since the operational performance of freeway segment and its neighboring local streets are often mutually dependent, a large body of literature related to concurrent control of the freeway and local arterial has been reported over the past decades. Most of such studies, however, focused on the on-ramp metering controls and their coordinated operations (Pooran and Lieu, 1994; Tian et al., 2002; Lu et al., 2013). A comprehensive review of such studies can be found in the study by Papageorgiou and Kotsialos (2000).

In contrast, the equally critical issue of off-ramp control has not yet received adequate attentions. As described by Lovell (1997), most drivers tend to not segregate themselves by destination well in advance of an off-ramp, but rather make most of their lane-changing decisions at the last moment. The exit queue of an off-ramp might spread itself laterally upstream of an off-ramp, thereby restricting the efficiency of the mainline flow. Hence, congested conditions at downstream intersections can lead to a long traffic queue at the off-ramp. Consequently, the queue spillback may propagate to upstream and block freeway lanes (Daganzo et al., 1999; Muñoz and Daganzo, 2002; Jia et al., 2004). Considering a partial blockage of the right lane, Newell (1999) proposed a model to evaluate the delays on a freeway when queues from an exit ramp spill back to the freeway mainline. Cassidy et al. (2002) studied the exiting queue of an off-ramp using field data from video-tapes, and find that a bottleneck with a diminished capacity arises on a

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freeway segment whenever queues from a segment's off-ramp spilled over and occupied its mandatory exit lane.

To mitigate the freeway congestion caused by excessive off-ramp queue, a category of studies aims to reduce the lane-change maneuvers near the off-ramps. For example, Daganzo et al. (2002) presented a dynamic lane assignment strategy to reduce the frequency of lane-changing maneuvers at the congested off-ramp areas. Based on the field observations, Rudjanakanoknad (2012) proposed two traffic control strategies to increase the off-ramp capacity in the congested area: off-ramp control and prohibiting lane change maneuvers near the off-ramp. To account for drivers' queue-jump behavior at the entry of an off-ramp, Di et al. (2013) proposed a cellular automata-based simulation model to evaluate different configurations of pavement markings around off-ramps. With the same purpose, another category of studies aims to detour the flows to other non-congested areas. For example, Günther et al. (2012) proposed a model to detour some vehicles on the surface streets, and offer the control priority to the off-ramp flows. Hence, their model intends to benefit the off-ramp flows at the expense of surface street users. Spiliopoulou et al. (2013) developed a real-time route diversion model from the user-optimum perspective. Given a detected off-ramp queue spillback, the control module will be executed to detour some off-ramp flows to an alternative route, aiming to prevent queue spillback at off-ramps. Since drivers may ignore the detour instructions, Spiliopoulou et al. (2013) further proposed another control model that calls for temporary off-ramp closure to force the route diversion.

Aside from the aforementioned strategies, a more efficient way to mitigate such off-ramp queue spillover is to control the traffic signals at its connecting local arterial. In review of the literature, it is noticeable that considerable studies have been done on optimizing the corridor control for freeway off-ramp and local arterials. For examples, Messer (1998) provided a control strategy and simulation study to solve traffic congestion at a closely-spaced signalized arterial which has a short distance between its intersections and the interchange exit. Along the same line, Tian et al. (2002) developed an integrated control algorithm, including ramp metering and local signal timings, to improve the performance of a freeway diamond interchange and its neighboring surface street. Li et al. (2009) presented a mixed-integer model for an integrated control between the off-ramp and arterial traffic flows, intending to minimize the queue spillback from an off-ramp to its the freeway mainline. Similarly, Lim et al. (2011) proposed a signal control model to minimize the total delay for off-ramps and their connected arterials. Pei and Zhou (2013) developed a control model to optimize the green time and cycle length at a surface road, based on the off-ramp traffic conditions. Using a two-stage framework, Yang et al. (2015b) proposed a decomposition control model to optimize the intersection signal timings and to concurrently provide signal progression to the competing traffic flows which comes from off-ramps and upstream intersections. In addition, Tian (2007) modelled an integrated control system for a freeway on-ramp and its upstream diamond interchange. The core logic of this study is to control the ramp feeding traffic from the diamond interchange with time-varying signal timings.

Despite the significant research advances reported in literature, several critical issues on this subject remain unsolved. For instance, due to the fluctuation of freeway traffic and the stochastic arrival rate at the off-ramp, an integrated corridor control with pre-timed strategies may not be sufficiently responsive. Using the real-time information, Yang et al. (2014b) provided a control system to prevent the queue spillback at freeway off-ramps. When the potential spillback is predicted, a signal priority with green time extension will be provided to the off-ramp flows, allowing the traffic to quickly pass the downstream intersections. Based on the simulation experiments, the study has demonstrated its effectiveness in preventing off-ramp queue spillovers. However, such system my potentially bring negative impacts to local traffic, and thus may justify the need to implement a complimentary responsive control, such as adaptive signal control which can benefit local intersections.

Using the real-time detected data, adaptive signal control is to dynamically adjust the signal plans and consequently improve the operational efficiency at local intersections. In review of literature, a lot of well-developed systems have been promoted by the transportation researchers. For instance, the Transportation Research Laboratory (Hunt et al., 1982; Day et al., 1998) developed the SCOOT (Spite Cycle and Offset Optimization Technique) system to minimize a pre-defined Performance Index, with the detected data in the form of Cyclic Flow Profiles (CFP). The Sydney Coordinated Adaptive Control System (SCATS), developed by the Department of Main Roads NSW, is a centralized hierarchical signal control system (Lowrie, 1990). Optimized Policies for Adaptive Control (OPAC) is a distributed real-time traffic signal control system that continuously adapts signal timings to minimize a performance function, based on the total intersection delay and vehicle stops over a pre-specified horizon (Gartner, 1983; Gartner et al., 1995; Gartner et al., 2001, 2002). The Real-time Hierarchical Optimizing Distributed Effective System (RHODES) uses a three-level hierarchy to characterize and manage traffic, which can explicitly predict traffic at these levels based on detector and other sensor information (Mirchandani and Head, 2001; Mirchandani et al., 2000). Other well-developed adaptive control systems include PRODYN (Henry et al., 1983) and UTOPIA (Mauro and Di Taranto, 1989).

Following the same line, this study intends to develop a control system which integrates the off-ramp priority control and adaptive signal control at local intersections. To tackle traffic congestions at local intersections so as to prevent the off-ramp queue spillover, the proposed system has been designed with three core control functions: off-ramp queue length estimation, arterial adaptive control, and off-ramp priority control. Specifically, the off-ramp queue length estimation function is used to predict whether a potential queue spillover will occur in the following signal cycle. Based on the detected flow data, the arterial adaptive control system will dynamically adjust intersection signal timings and offsets to reduce the intersection delay as well as provide signal progression to those heavy path-flows. When potential queue spillover is predicted, the off-ramp priority control function will be activated to offer green extension and progression priority to the off-ramp flows.

The remaining part of this paper is organized as follows: the next section will introduce the research background with some field observations and the system framework; Section 3 will introduce the off-ramp queue estimation model; Sections 4 and 5 will illustrate the formulations of adaptive control and off-ramp priority control functions; Section 6 will present the numerical example results and some conclusions along with future research directions will be provided in the last section.