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# Stochastic modeling of the dynamics of incident-induced lane traffic states for incident-responsive local ramp control

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**Abstract**

Incident-induced traffic congestion has been recognized as a critical issue to solve in the development of advanced freeway incident management systems. This paper investigates the applicability of a stochastic optimal control approach to real-time incident-responsive local ramp control on freeways. The architecture of the proposed ramp control system embeds two primary functions including (1) real-time estimation of incident-induced lane traffic states and (2) dynamic prediction of ramp-metering rates in response to the changes of incident impacts. To accomplish the above two goals, a discrete-time nonlinear stochastic optimal control model is proposed, followed by the development of a recursive prediction algorithm. Based on the simulation data, the numerical results of model tests indicate that the proposed method permits relieving incident impacts particularly under low-volume and medium-volume conditions, relative to high-volume lane-blocking conditions. Particularly, the incident-induced queue lengths can be improved by 50.1% and 67.9%, compared to the existing ramp control and control-free strategies, respectively.
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*Keywords:* Incident-induced lane traffic behavior; Stochastic optimal control; Incident management

## 1. Introduction

Incident-induced traffic congestion has been recognized as a critical problem to solve in the development of advanced freeway traffic management systems. It is generally agreed that lane-blocking incidents on freeways interrupt traffic flows unexpectedly, and are also a major cause of over-congestion that contributes readily to bottlenecks. During a lane-blocking incident, the time-varying traffic demand continues to exceed the reduced link capacity, and meanwhile, the growing incident-induced lane changes and queue lengths upstream to the incident site significantly interrupt the traffic flows among adjacent lanes. As a consequence, the existing freeway traffic control and management systems may malfunction owing to the lack of capability to respond appropriately to incident impacts. Theoretically, traditional freeway traffic control strategies such as tactical reduction in on-ramp flow rate and breaking the platoons of the entering vehicle to facilitate vehicular merging

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in weaving areas can be ineffective under conditions of over-congestion which is a typical traffic phenomenon of lane-blocking incidents on freeways.

Despite the awareness that ramp-metering control has been extensively used as a fundamental mechanism to improve freeway traffic operations, and various ramp-metering control technologies have been proposed for either local operations [1–8] or system coordination [9–15], there seems to remain a lack of research on exploring real-time technologies to address the issues of time-varying incident impacts on ramp-metering control. The investigations by Shaw and McShane [2] can be regarded as a pioneering study in incident-responsive ramp control, where they formulated the problem of traffic jams at the incident site with a deterministic queuing theory-based model. Given the incident duration as well as some other ideal assumptions, Shaw et al. proposed to compare the predicted waiting time of any given on-ramp traffic arrival with a predetermined threshold to determine whether or not the new arrival is allowed to enter the freeway. The demand-capacity and percent-occupancy strategies [3,4] which are the two typical ramp control modes used in the USA, and claimed to be incident-responsive, are based essentially on the same fundamental that the measurements such as volumes and occupancies upstream to the ramp under control are compared to preset thresholds to determine the ramp-metering rate. While under conditions of lane-blocking incidents, the determination in terms of these fixed thresholds may turn out to be a critical issue remaining in the aforementioned two traffic-responsive control algorithms due to the variety of incident-induced traffic flow patterns. To deal efficiently with the variety of freeway traffic congestion conditions including nonrecurrent congestion cases [10] Chen et al. proposed an ingenious ramp control strategy employing fuzzy control theories. In comparison with the existing controllers at the study site under limited six incident scenarios, their test results implied that it is promising to gain higher ramp control efficiency with quick response to various incident cases via refined strategies. Wang [16] proposed to use a linear programming method together with a moving-average technique to formulate the problem of ramp-metering control in response to nonrecurring congestion situations, where the ramp control rate was updated per 5 min in his approach to reduce incident impacts on mainline capacities of freeways. Rooted in a three-phase traffic theory, Kerner [8] proposed a congested pattern control approach (ANCONA) to address the issue of congestion propagation upstream from a freeway bottleneck. Although the potential advantages of Kerner's model were demonstrated in comparison with the well-known ALINEA[1] approach, the suitability of the embedded lane-changing rules used for diverse lane-blocking incident cases and the resulting effects on real-time ramp control performance were not investigated in Kerner's study. In addition, a number of ALINEA-based ramp control approaches were continuously proposed [5,7,14], and however, nonrecurrent congestion problems caused by lane-blocking incidents on freeways remained unsolved in these studies.

Apparently, real-time incident-responsive ramp control warrants further research to accomplish. As pointed out in Sheu et al. [17], integrating the functions of real-time incident impact prediction and incident-responsive traffic control is a critical stage in freeway congestion management. Furthermore, the gap between ramp control and freeway incident management still remains in the previous literature for the lack of sophisticated incident-induced traffic prediction models to dynamically characterize incident impacts in the process of ramp-metering control. For instance, the efficiency of the method by Wang stated previously relies to a great extent on the accuracy in the estimation of aggregated vehicular travel time spent to go through the mainline detection zone while the effects of incident-induced lane traffic maneuvers such as lane changing and queuing may be ignored in this approach. Similar problems can also be found in the other ramp control strategies noted above.

Accordingly, rooted in the stochastic optimal control methodology, this paper presents a new approach to real-time incident-responsive local ramp control. Under conditions of lane-blocking incidents on freeway mainline segments, local ramp-metering control is formulated as a stochastic optimal control problem with the goal of minimizing the incident impacts upstream to the incident spot. The most distinctive feature of the proposed control method is that the dynamics of incident-induced inter-lane and intra-lane traffic states as well as incident impacts can be estimated in real time, and then used as the parameters in the time-varying objective function to serve specific control purposes during lane-blocking incidents. The details of the primary procedures involved in the development of the proposed methodology and preliminary tests are described in the following sections.

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[1] ALINEA is the acronym for "Asservissement LINEeaire d'entree Autoroutiere" French for "linear ramp metering control."

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