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Physica A 387 (2008) 4327–4348

PHYSICA A

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An integrated toll and ramp control methodology for dynamic freeway congestion management

Jiuh-Biing Sheu[a,*], Hai Yang[b,1]

[a] Institute of Traffic and Transportation, National Chiao Tung University, 4F, 114 Chung Hsiao W. Road, Sec. 1 Taipei, Taiwan
[b] Department of Civil Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

Received 19 September 2007; received in revised form 7 February 2008
Available online 25 February 2008

Abstract

This paper investigates an integrated freeway traffic management system, which coordinates both dynamic toll pricing and ramp control strategies for the purpose of dynamic freeway congestion management. The proposed integrated dynamic toll-ramp control methodology is built mainly on the principles of stochastic optimal control approaches, involving two developmental procedures. First, through detector configurations and system specification, a discrete-time nonlinear stochastic system is formulated to characterize the time-varying relationships of system states, control variables, and traffic data. Then, by employing the extended Kalman filtering technology, a stochastic optimal control based algorithm is proposed to execute the integrated dynamic toll and ramp control mechanism. With the aid of the Paramics microscopic traffic simulator, numerical studies under various simulated freeway congestion scenarios are conducted. Corresponding numerical results demonstrate the applicability of the proposed methodology in response to diverse freeway traffic congestion phenomena, and its relative advantages in improving both the average travel time and hourly throughputs by 16.4% and 16.5%, respectively.

Keywords: Stochastic system modeling; Dynamic toll pricing; Ramp control; Stochastic optimal control

1. Introduction

Despite the fact that numerous advanced technologies have emerged in the form of intelligent transportation systems (ITS) to solve freeway traffic congestion problems, freeway traffic congestion management remains a critical issue in ITS. Here congestion management refers to a comprehensive decision-making process to identify and control traffic congestion via traffic control and management strategies with the goal of enhancing traffic safety and mobility. As is increasingly recognized, the difficulties of managing freeway traffic congestion are mainly rooted in the dynamics of congestion patterns, including recurrent and non-recurrent congestion patterns on mainline segments, and limited information in terms of en-route drivers' maneuvers responding, in real time, to both traffic congestion conditions and corresponding freeway traffic management strategies when approaching on-ramps. As a result, freeway

* Corresponding author. Tel.: +886 2 2349 4963; fax: +886 2 2349 4953.
E-mail addresses: jbsheu@mail.nctu.edu.tw (J.-B. Sheu), cehyang@ust.hk (H. Yang).
[1] Tel.: +852 2358 7178; fax: +852 2358 1534.

0378-4371/$ - see front matter
doi:10.1016/j.physa.2008.02.049

traffic flows and congestion patterns turn out to be more complicated and uncontrollable in the ITS operational environment. For instance, provision of the real-time toll rates and corresponding traffic congestion information via ITS technologies seems to influence drivers' decisions of route choice to a certain extent. However, our perception of drivers' instantaneous responses to the corresponding traffic operational environment is quite limited, thus contributing to the difficulty in determining appropriate congestion tolls in real time, as well as ramp control strategies to alleviate freeway traffic congestion, efficiently and effectively.

Accordingly, to regulate traffic entering a freeway in response to the variability of freeway traffic congestion, both dynamic on-ramp metering control and toll collection appear to be two promising measures to manage freeway congestion. Nevertheless, there seem to be some arguments in terms of the limitations of the existing technologies used for freeway congestion management. Some typical examples are illustrated below for discussions.

Ramp control arises from the idea of controlling on-ramp traffic flows entering mainline segments of freeways via ramp metering so as to achieve given objectives for freeway traffic management [31,20]. More recently, a variety of sophisticated methodologies, including optimal control theories [1,39], artificial intelligence [2,38], and hybrid traffic flow-control approaches [40,41] have been proposed to improve the system performance of either local ramp control or multiple ramp control. Despite the distinctive features of these existing ramp control models, apparently, there is a developmental trend that the mechanisms of ramp control seem to be more responsive to short-term changes of traffic demands in the temporal domain, and more adaptable to integrate with other external methodologies for large-scale congestion management in the spatial domain.

Although there have been a certain advances in exploring ramp control methodologies for freeway traffic control, there seem to be some arguments remaining over the performance of ramp control under high congestion conditions. This argument holds particularly in queue-overflowing and lane-blocking incident cases. In reality, such phenomena are comprehensible due to the fact that unlike signal control on surface streets, the effect of ramp control is mainly on the entry traffic volume rather than on the mainline volume of a freeway. Without other traffic management strategies to divert either on-ramp or mainline traffic flows, the performance of ramp control may turn out to be insignificant in case where the mainline traffic loads are sufficiently greater than the on-ramp traffic loads in a given segment.

In contrast, road congestion pricing including freeway electronic toll collection (ETC) systems has been increasingly recognized as an effective traffic management strategy to manage regional peak-hour road congestion [29,12,8,15]. As pointed out in [7], considering the trade-off between out-off-pocket travel costs and delays, road users may respond to the instantaneous toll rates before entering the instrumented toll collection systems by modifying their travel behavior including diverting routes, departing at a different time and switching modes of transport. Under such a postulation, a great many researchers have made efforts on the investigation of congestion pricing theories and toll collection strategies [30,9,26,10,37,33,13]. Therein, numerous pioneer researchers advocate utilizing the principle of marginal-cost pricing to deal with the optimal congestion pricing problem and its potential impacts on traffic flows. Three fundamental elements, including the speed-flow relationship, the demand function, and the generalized cost, which affect the implementation of congestion pricing systems, were investigated [5,11,34,35,32,4,3,14,17]. Furthermore, considering the impracticability of searching for the first-best pricing solutions, diverse second-best pricing regimes, including the cordon-based second-best pricing, were proposed for real-world applications [15,28, 33,40,41].

Accordingly, the existing congestion pricing theories appear promising in addressing freeway congestion management issues. Nevertheless, the use of ETC for dynamic freeway congestion management may still warrant more research efforts due to the following concerns. First, the applicability of the existing marginal-cost congestion pricing theories may hold only under certain traffic flow conditions, e.g.,low-volume and medium-volume conditions. It can be seen in most of the previous literature, the corresponding average social cost curve is assumed to be strictly increasing with traffic flow without considering the link capacity issue. Consequently, a downhill-shape speed-flow curve is extensively used to determine the optimal congestion toll as well as the effects of congestion pricing on traffic flows. Obviously, the aforementioned postulation may not be applicable for highly congested cases where the speed-flow curve becomes backward bending after the maximum traffic flow point, as shown in any fundamental diagrams of traffic flow-speed-density. Similar arguments can also be found elsewhere [11]. Second, the use of aggregate demand functions in characterizing individual drivers' maneuvers responding to toll rates may remain problematic in the dynamic congestion management context. From an aggregate economics point of view, it seems more agreeable that those toll rates derived from the marginal-cost congestion pricing theories may apply merely for long-term and large-scale congestion pricing cases, where the features of system-wide road users and the