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An iterative learning approach for density control of freeway traffic flow via ramp metering

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Abstract

In this work, we apply the iterative learning control approach to address the traffic density control problem in a macroscopic level freeway environment with ramp metering. The traffic density control problem is first formulated into an output tracking and disturbance rejection problem. Through rigorous analysis, it is shown that the iterative learning control method can effectively deal with this class of control problem and greatly improve the traffic response. Next, the iterative learning control is combined with error feedback in a complementary modular manner to achieve the output tracking and system robustness. The effectiveness of the new approach is further verified through case studies with intensive simulations.

Keywords: Freeway traffic control; Traffic density control; Iterative learning control; Ramp metering; Macroscopic traffic flow

1. Introduction

Freeway traffic control becomes ever increasing important in the field of traffic engineering, because of the rapid development of freeway infrastructure and the fast increasing traffic demand in metropolitan areas in both developed and developing countries. Among various freeway traffic control methods, ramp metering provides an efficient traffic management on freeways and freeway networks (Papageorgiou and Kotsialos, 2002). Ramp metering is a general term describing all techniques that restrict the access to freeway through the on-ramps. The ramp metering, if properly applied, can regulate the amount of traffic that enter a given freeway at its entry ramps, so that the freeway can operate at the desired level of service and avoid any traffic congestion. Generally speaking, ramp metering will be effective when traffic is not too light (otherwise ramp metering is

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not needed) and not too dense (otherwise breakdown will happen anyway). In practice, ramp metering is implemented by placing a traffic light at the on-ramp that allows vehicles to enter the motorway in a controlled manner and thus regulates traffic in the mainline.

From the viewpoint of a freeway administrative agent, it is imperative to design an appropriate control mechanism for ramp metering such that the traffic entering the freeway does not incur overflow or underflow. Overflow means that the freeway is over utilized and accidents or congestion may easily occur. Underflow means a low utilization rate of the freeway, which is not cost effective. From the viewpoint of system control, this is a typical set-point problem and numerous control methods have been exploited, e.g. mathematics programming or similar formulations (Wattleworth, 1965; Yuan and Kreer, 1971; Cheng et al., 1974; Papageorgiou, 1980); LQR (Isaken and Payne, 1973); decentralized control (Golstein and Kumar, 1982); PID-like controller (Masher et al., 1975; Papageorgiou et al., 1991); one-step ahead prediction and multi-step prediction adaptive control (Ji, 1996); function approximation based on neural network (Zhang et al., 2001; Zhang and Ritchie, 1997); non linear integrator backstepping (Chien et al., 1997); linear and nonlinear feedback control (Chang and Li, 2002; Kachroo and Ozbay, 2003); optimization and optimal control theory (Alessandri et al., 1998; Parageorgiou et al., 1990; Zhang and Recker, 1999; Kotsialos et al., 2002), etc. Those methods, according to Papageorgiou and Kotsialos (2002), can be further classified into three strategies: fixed-time strategy, locally actuated control strategy and system control strategy. The fixed-time strategy is based on a simple and static traffic model together with historical data; the locally actuated control strategy acts in real time on the basis of traffic conditions in the immediate vicinity of the on-ramp; and the system control strategy calculates a new metering action according to real-time freeway traffic conditions of the entire traffic system in every time interval. It was reported that the local control strategy is far easy to design and implement, and proven to be noninferior to more sophisticated coordinated approaches under recurrent traffic congestion conditions (Papageorgiou and Kotsialos, 2002). Therefore in this work we will develop a new local actuated control method base on recurrent traffic conditions.

Due to the limited means in freeway measurement, the integer number of vehicles on freeway, and the complexity in freeway traffic, discrete traffic flow models are widely accepted and used. The discrete nature of model and control, however, prevents the use of high gain feedback in ramp metering. As such, the feedforward compensation provides an alterative way in problem solving. Model based predictive control, Kalman filter and other state estimation methods require an accurate model. Besides, those methods are difficult to design and construct for nonlinear processes. In practice, an accurate freeway traffic model is hardly available in practice and it is highly nonlinear. We need a simple and robust feedforward control method that is insensitive to modeling uncertainties and suitable for nonlinear dynamics. Iterative learning control (ILC) is suited for this kind of control problems.

It is worth to point out that macroscopic traffic flow patterns are in general repeated every day though they vary in the time-of-day. For instance, the traffic flow will start from a very low level in the midnight, and increase gradually up to the first peak during morning rush hour, which is often from 7 to 9 AM, and the second peak from 5 to 7 PM. Ruling out the occasional occurrence of accidents, the routine traffic flow on freeway in the macroscopic level will show inherent repeatability everyday. We may easily find that, traffic flow patterns in two consecutive days, or the same weekday of two consecutive weeks, are very close. Likely we can find the similarities on a monthly basis, or even a yearly basis. In fact, the traffic repeatability is implicitly assumed in all fixed-time (time-of-day/pre-time) traffic control methods.

A limitation of many existing traffic control methods, whether feedback or feedforward dominant, is the lack of capability to learn and improve the control performance from a recurrent traffic process. Without learning, a control system can only produce the same performance without improvement even the process is repeated once again. The idea of ILC is straightforward: use control information of the preceding execution to improve the present execution.

Iterative learning control (ILC) was first proposed by Arimoto et al. (1984) for control problems repeated over a finite interval. Since then, ILC has been extensively studied with significant progress in both theory and applications (Xu, 1997; Chien, 1998; Chen and Wen, 1999; Xu and Tan, 2003). ILC has a very simple structure consisting of an integral like updating law along the iteration axis and a memory array to store information of previous iterations. It requires very little system modeling knowledge, in fact only the bound of the direct transmission term of the system input/output is needed to guarantee the learning convergence. Thus it is