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Dynamic traffic metering in urban street networks: Formulation and solution algorithm

Rasool Mohebifard, Ali Hajbabaie*

Department of Civil and Environmental Engineering, Washington State University, United States

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ABSTRACT

Traffic metering offers great potential to reduce congestion and enhance network performance in oversaturated urban street networks. This paper presents an optimization program for dynamic traffic metering in urban street networks based on the Cell Transmission Model (CTM). We have formulated the problem as a Mixed-Integer Linear Program (MILP) capable of metering traffic at network gates with given signal timing parameters at signalized intersections. Due to the complexities of the MILP model, we have developed a novel and efficient solution approach that solves the problem by converting the MILP to a linear program and several CTM simulation runs. The solution algorithm is applied to two case studies under different conditions. The proposed solution technique finds solutions that have a maximum gap of 1% of the true optimal solution and guarantee the maximum throughput by keeping some vehicles at network gates and only allowing enough vehicles to enter the network to prevent gridlocks. This is confirmed by comparing the case studies with and without traffic metering. The results in an adapted real-world case study network show that traffic metering can increase network throughput by 4.9–38.9% and enhance network performance.

1. Introduction

Metering traffic on on-ramps can improve traffic operations on freeway facilities by maintaining traffic state in undersaturated flow conditions and avoiding capacity loss at the expense of delaying vehicles entering the freeway from on-ramps (Papageorgiou and Kotsialos, 2000; Cassidy and Rudjanakanoknad, 2005; Hegyi et al., 2005; Gomes et al., 2008; Papamichail et al., 2010; Pasquale et al., 2015). The same concept offers great potential to improve traffic operations by regulating/limiting the flow of vehicles into congested areas of urban street networks (Roess et al., 2011; Hajbabaie, 2012; Aboudolas and Geroliminis, 2013).

In congested conditions, queue-spill overs and gridlocks reduce the capacity of urban street networks to process vehicles and consequently increase the total travel time. The macroscopic fundamental diagram (MFD) for an urban street network (Mahmassani et al., 1984; Daganzo, 2007; Geroliminis and Daganzo, 2008) suggests that an optimal accumulation level of vehicles inside a network exists that maximizes the network throughput. Accordingly, increasing the network inflow to a degree that the number of vehicles inside the network surpasses the optimal accumulation level decreases the network throughput (Daganzo, 2007) due to queue spillovers and gridlocks inside the network. In this condition, controlling the number of entry vehicles can reduce traffic congestion and allow the network to process as many vehicles as possible.

Traffic metering can be used to protect congested areas of urban street networks from oversaturated flow conditions. Metering signals, similar to those implemented on on-ramps, can be placed at the borders of the congested areas to regulate the number of

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* Corresponding author.
E-mail address: ali.hajbabaie@wsu.edu (A. Hajbabaie).

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incoming vehicles. Hereafter, we call these signals network gates. These gates should be sited at locations with enough capacity to hold metered vehicles.

Available traffic metering approaches for urban street networks either fail to provide dynamic optimal metering levels or rely on well-defined MFD, which cannot be derived easily for heterogeneous networks without decomposing them to homogeneous subnetworks (Mazloumian et al., 2010; Geroliminis and Sun, 2011). Besides, such diagrams are prone to change if network characteristics, such as signal control parameters, change (Laval, 2010).

This study fills this knowledge gap by finding optimal metering levels at each individual gate of an urban street network dynamically without the need for MFD diagrams. This paper presents two mathematical programs based on the Cell Transmission Model (CTM) (Daganzo, 1994, 1995) to maximize the number of completed trips in transportation networks by only regulating the incoming flow rates at network gates. The first mathematical program is linear and consequently can be solved efficiently in medium size networks. However, it has the flow holding-back problem, or if viewed from a different angle, has the capability of metering the flow inside the network at every cell. The paper also proposes a Mixed Integer Linear Program (MILP) that limits metering only to the network entry gates. Besides, a novel solution algorithm is developed to solve the MILP efficiently by converting it to a linear programming model and several CTM simulation runs.

In the remainder of the paper, a review of relevant literature on traffic metering in urban street networks is presented. Problem formulation is elaborated next and the solution technique is detailed. After a brief description of the case study networks, results are discussed and concluding remarks are presented.

2. Literature review

2.1. Scenario-based traffic metering

Scenario-based approaches study the effects of traffic metering on network performance based on predefined metering levels at network entry gates. Rathi and Lieberman (1989) explored the effects of metering traffic in a simulated network representing portion of traffic grid in Manhattan, New York. Different entry volumes were selected with the assumption that these vehicles had already passed the metering point, and the metering effects outside the cordon could not be directly measured. Results showed that metering could be beneficial in reducing delay and increasing throughput, and studies to further investigate the effect of metering strategies were recommended.

Hajbabaie and Benekohal (2011) explored the operational effects of metering traffic at the perimeter of an urban street network. They tested several metering rates and optimized the timing of signalized intersections for each rate to eliminate the impacts of sub-optimal signal timing parameters on network performance. They did not propose an optimal metering strategy; however, showed that an optimal metering threshold exists that yields more efficient network performance than a no-metering strategy, by keeping flows just below the saturation level and avoiding gridlocks. Medina et al. (2013) confirmed the previous findings by analyzing a fixed metering rate over time at network gates and concluded that using dynamic traffic metering could offer better network performance. These studies showed that traffic metering can be added to conventional traffic signal timing strategies as another layer of control in urban street networks. However, scenario-based approaches do not provide optimal metering rates dynamically.

2.2. MFD-based traffic metering

On the other hand, some studies have focused on developing dynamic control strategies by assuming a network-wide relationship between the number of vehicles inside a network and network throughput, which is referred to as Macroscopic Fundamental Diagram (MFD). Godfrey (1969) introduced the concept of a network MFD, Daganzo (2007) discussed the application of the MFD concept to traffic metering, and Geroliminis and Daganzo (2008) provided empirical verifications of existence of such diagrams for an urban area in Yokohama, Japan. Using the MFD concept, Daganzo (2007) suggested that a relationship exists between vehicle accumulation inside a network and the output flow. He presented the relationship as a generic exit function that showed that maximum network throughput was achievable when a certain number of vehicles were inside the network. He also reasoned that an optimal control strategy existed when the number of vehicles inside a network was within the optimal accumulation limits with two assumptions: (a) the network should be homogenous in terms of density, and (b) network demand should evolve slowly over time.

While Daganzo (2007) did not suggest a practical implementation of traffic metering, Keyvan-Ekbatani et al. (2012) exploited the MFD concept and designed a control model and a feedback control structure for metering vehicles at network gates. They found optimal vehicle accumulation for a sample network by simulating the network in a microscopic simulation environment. By setting the optimal range in the proposed feedback controller, they showed sensible improvements in the network performance. Further development of the feedback-based gating model is discussed in Keyvan-Ekbatani et al. (2015). This study enhanced the previous model to account for gate signals placed upstream of the protected network area and not exactly at its borders. Remote signals added extra travel time to vehicles traveling between the gate signals and the border of the study region. This travel time was considered as the time delay in the feedback controller. Haddad and Shraiber (2014) argued that a simple feedback controller could regulate traffic just near the optimal vehicle accumulation setpoint; however, network behavior varied significantly across multiple urban regions, thus traffic scenarios were too diverse to depend on a reliable optimal vehicle accumulation setpoint.

While the discussed MFD-based control algorithms assumed that density was homogenous in the network, some studies (Aboudolas and Geroliminis, 2013; Ramezani et al., 2015; Kouvelas et al., 2017) developed control strategies for a heterogeneous network by dividing it to several homogenous regions, each with a well-defined MFD. The objective of dividing a network is to have