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Real-time traffic network state estimation and prediction with decision support capabilities: Application to integrated corridor management

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ABSTRACT

This paper presents a real-time traffic network state estimation and prediction system with built-in decision support capabilities for traffic network management. The system provides traffic network managers with the capabilities to estimate the current network conditions, predict congestion dynamics, and generate efficient traffic management schemes for recurrent and non-recurrent congestion situations. The system adopts a closed-loop rolling horizon framework in which network state estimation and prediction modules are integrated with a traffic network manager module to generate efficient proactive traffic management schemes. The traffic network manger adopts a meta-heuristic search mechanism to construct the schemes by integrating a wide variety of control strategies. The system is applied in the context of Integrated Corridor Management (ICM), which is envisioned to provide a system approach for managing congested urban corridors. A simulation-based case study is presented for the US-75 corridor in Dallas, Texas. The results show the ability of the system to improve the overall network performance during hypothetical incident scenarios.

1. Background

Traffic congestion has reached alarming levels in most urban areas as depicted by excessive travel delays, poor environmental quality and increasing traveler frustration. With the limited ability to expand the physical capacity of the roadway network to meet the growing travel demand, there are increasing calls to develop advanced traffic network management systems to achieve efficient utilization of the existing network capacity. Such systems are envisioned to provide traffic network managers with decision support capabilities through developing efficient traffic management schemes that integrate a wide range of traffic control and traveler information provision strategies. Nonetheless, developing such capabilities requires modeling the traffic network at high fidelity by capturing the temporal and spatial demand-supply interactions and associated congestion phenomena. Considering their numerous applications, simulation-based Dynamic Traffic Assignment (DTA) models have proved to be a valuable tool for modeling congestion dynamics in large-scale urban transportation networks (Wirtz et al., 2005; Sisiopiku et al., 2007; Brinckerhoff, 2012; Donnelly et al., 2010). As such, extensive research effort has

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been devoted to extending the capabilities of these models for real-time traffic management applications. In addition, effort is dedicated to developing other essential complementary modules including Origin-Destination (OD) demand estimation and prediction (e.g., Sherali and Park, 2001; Bierlaire and Crittin, 2004; Antoniou et al., 2007; Zhou and Mahmassani, 2006, 2007; Etemadnia and Abdelghany, 2010, 2011), traffic data fusion and consistency checking (e.g., Doan et al., 1998; Peeta and Bulusu, 1999; Zhou and Mahmassani, 2005; Wang and Papageorgiou, 2005; Alnawaiseh et al., 2014; Hashemi and Abdelghany, 2015a; Hashemi et al., 2016), and optimal traffic management schemes (e.g., Mirchandani and Head, 2001; Park et al., 1999; Abu-Lebdeh and Benekohal, 2003; Ceylan and Bell, 2004; Varia and Dhingra, 2004; Lee et al., 2005; Sun et al., 2006).

The two pioneer systems, DYNASMART-X and DYNAMIT, are examples of simulation-based real-time DTA traffic network management systems (Mahmassani, 2001; Chen et al., 2015; Ben-Akiva et al., 2001, 2012; Milkovits et al., 2010). They provide capabilities for real-time traffic network state estimation, short-term prediction of congestion dynamics, and traffic network management. A review of similar systems with short-term traffic network state prediction capabilities and other methodologies for traffic state prediction can be found in Barros et al. (2015) and Hashemi and Abdelghany (2015b). Developed traffic management strategies using these systems have focused primarily on providing either descriptive or normative route guidance strategies for travelers (e.g., Peeta and Mahmassani, 1995; Hawas and Mahmassani, 1996; Peeta and Zhou, 2002). Most effort to develop integrated traffic management schemes that incorporate multiple management strategies such as pre-trip and en-route traveler information provision, optimal signal timing, ramp metering, dynamic shoulder lanes, and congestion pricing has been presented only using offline platforms. For example, Abdelfatah and Mahmassani (1998) presented a modeling framework for solving the system optimal time-dependent path assignment and signal timing. While the solution provides a benchmark for similar traffic management strategies, the assumption that all drivers comply with the provided normative route guidance is unrealistic. In addition, the developed solution algorithm is computationally cumbersome which precludes its application in real-time. Abdelghany et al. (1999) introduced the path-based signal coordination strategy to provide additional capacity along dominant routes used by travelers diverted from the freeway due to accidents. A traffic network prediction module is used to determine the dominant diversion routes along which coordination is provided. However, the presented experiments were limited to a simplified network with few alternative diversion options. In more recent work, Chen et al. (2015) presented a framework similar to the one presented in paper with focus on evaluating the effectiveness of signal timing plans with coordination for adverse weather conditions. However, the system assumes that a set of timing plans are pre-defined and the system picks one of these plans. Aboudolas et al. (2010) presented a rolling-horizon quadratic programming approach to the signal control problem. The main goal is to minimize and balance queue to prevent queue spillback. Mirchandani and Head (2001) developed a real-time traffic signal control system based on adaptive signal timing using a hierarchical architecture. The system predicts traffic flow at appropriate resolution levels to enable proactive control. Choy et al. (2003) presented a cooperative, hybrid agent architecture for real-time traffic control. The network is assumed to be managed by multiple agents and a cooperative distributed problem solving approach is considered to achieve coordination between the different agents. Lee et al. (2005) proposed an optimization approach for real-time adaptive traffic signal control using a genetic algorithm. The adaptive system generates efficient signal timing strategies to respond to changing tempo-spatial traffic demand. The system is not evaluated in oversaturated conditions as it lacks the capability to adequately present queue spillback from adjacent intersections. Etemadnia and Abdelghany (2012) presented a distributed autonomic architecture for real-time traffic network management. The architecture assumes multiple controllers that could operate in teams. The prediction module is used to evaluate the team formation strategies to determine the best cooperation schemes among controllers. As for real-time congestion pricing strategies, Dong et al. (2011) presented a congestion pricing framework for real-time freeway management. The model utilizes the network state prediction results in order to generate anticipatory pricing schemes that are consistent with the travelers' behavior. Hassan et al. (2013) presented a similar framework where the goal is to maximize the collected revenue for toll facilities operated under public-private partnership agreements. In a more recent work, Gupta et al. (2016) presented a framework to optimize the toll strategies using a meta-heuristic approach.

The literature review reveals that previous research work has primarily focused on either developing the architecture of real-time traffic management systems, or examining the effectiveness of different traffic management strategies under different operation conditions in offline simulation environments. Studies that focus on developing active decision support capabilities in the context of real-time traffic network management applications are infrequent in the literature (Aboudolas et al., 2010). In addition, limited effort is devoted to testing the effectiveness of traffic network strategies when integrated as part of decision support capabilities for real-time traffic network management systems. To our knowledge, research effort that is devoted to (a) developing real-time traffic management systems that are capable of generating integrated traffic management schemes; and (b) evaluating the performance of these systems for calibrated networks with reasonable sizes and for extended horizons has not been thoroughly presented in the literature. This paper aims at closing this gap by presenting a real-time traffic network management system with decision support capabilities. The system extends the capabilities of the DTA simulation-based model, DIRECT (Dynamic Intermodal Routing Environment for Control and Telematics), which was developed by researchers at Southern Methodist University (Hashemi and Abdelghany, 2015b). The system seeks to provide traffic network managers with the capabilities to estimate the current network conditions, predict congestion dynamics, and generate efficient traffic management schemes for recurrent and non-recurrent congestion situations. The system adopts a rolling horizon framework, which integrates network state estimation and prediction modules. The network state estimation module is in the form of a real-time simulation-based DTA model which is synchronized with the real clock and receives real-time