



A stochastic optimal control approach for real-time traffic routing considering demand uncertainties and travelers' choice heterogeneity



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ABSTRACT

This paper develops a theoretical approach to identify optimal traffic routing strategy for managing transportation systems. It obtains the optimal traffic diversion ratio to each route that can be achieved in real time through cutting-edge sensing and vehicle-infrastructure communication technologies. We minimize the expected total travel time of all travelers in the network by providing and updating routing advice (or incentives) to travelers in real time. The system-optimum traffic routing problem is modeled using the stochastic control approach where demand uncertainty and travelers' heterogeneity are explicitly considered over time. The approach is generic in the sense that the optimal routing strategies can be achieved through various technologies, such as connected vehicle technologies, navigation systems, variable message signs, dynamic pricing, etc. For a two-route representative network, we use dynamic programming to derive and approximate the analytical solution of the optimal routing policy for each time interval. The optimal diversion ratio can be updated solely upon the traffic counts measured along the preferred route in real time. The general rule is, with a high probability, to minimize the congestion and keep the maximum flow performance on the preferred route from the beginning of the peak hours. Towards the end of the peak hours, the optimal policy would allow more intensive use of the preferred route resulting over-saturation, whereas keeping the minimal use of the alternative route. The analytical solution is validated and examined in a synthesized network and a real-world network in California. It is found that it consistently outperforms the deterministic solution, and its resultant system performance is also reasonably close to the benchmark system optimum where true demand could be precisely known one day ahead.

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1. Introduction

Traffic management strategies aim to optimally allocating travelers to the under-utilized space and time such that the total system cost can be mitigated. One effective strategy is spatial demand allocation that can be achieved by real-time traffic routing. Those vehicles are advised with or directed to follow certain routes provided with real-time traffic information. The advancement of contemporary communication and sensing technologies in recent years enables

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effective real-time traffic routing through information provision in the connected vehicular networks, along with various user-specific incentives (such as dynamic pricing) (see reviews of Papageorgiou et al., 2003; Kiencke et al., 2006, also see Chen, 2013). This paper proposes a generic stochastic control approach for optimal real-time traffic routing considering demand uncertainty and travelers' choice heterogeneity. For a two-route network that approximates travelers choices of a heavily congested corridor over a local alternative route, we derive analytical solutions for system-optimal real-time traffic routing policies that are solely dependent on the real-time sensing. It provides modeling basis for general real-time traffic routing and control through various ways, such as road-side variable message signs (VMS), smart phone applications, navigation systems, congestion pricing, and other incentives. Ultimately, the traffic routing policy ensures the transportation system stay in the optimal condition in the real time.

Ample research studies have investigated providing real-time route guidance to individuals through radio messages, real-time travel time displayed on the road-side VMS (e.g., Wunderlich et al., 2000; Mammar et al., 1996; Messmer et al., 1998), navigation systems or smart phones (e.g., Aerde and Case, 1988). However, there is a lack of theories to provide information strategically, or optimally. Information provision does not necessarily lead to system optimum, and can controversially create congestion under some circumstances. Of few literature that uses real-time information provision to optimally allocate traffic flow, Adler et al. (2005) explored traffic management and dynamic routing problem using cooperative and distributed multi-agent systems, and found negotiation between drivers and information service providers can improve the network performance and increase driver satisfaction. Paz and Peeta (2009) explicitly took the drivers' reactions towards the real-time traffic information into account when seeking the controller to enhance traffic network performance, where a fuzzy control modeling approach is adopted to determine real-time traffic routing strategies. Kachroo and Özbay (1998) formulated the real-time dynamic traffic routing as a feed-back control problem and used feedback linearization technique to solve it, which aims to achieve a user-equilibrium traffic pattern. Similar to Du et al. (2014) modeling the online vehicle routing as mixed-strategy congestion game, Du et al. (2015a) proposed an on-line in-vehicle routing scheme with real-time information exchange among vehicles using pure-strategy atomic routing game model, namely a coordinated online in-vehicle routing mechanism (CRM). Du et al. (2015b) exploited bounded rationality of the travelers, they extended their CRM model to a coordinated online in-vehicle routing mechanism with intentional information provision perturbation (CRM-IP), in which user optimality and system optimality are balanced. In general, those studies examined optimal routing strategies based off heuristics or simulation (e.g., Wang et al., 2001; 2003; Pavlis and Papageorgiou, 1999; Levinson, 2003; Gao and Chabini, 2006; Hawas et al., 2012), while no analytical solution is obtained, nor system optimum is theoretically guaranteed.

Despite of existing research on real-time system-level traffic routing, two main issues are yet fully addressed. First, travelers' route choices can vary substantially provided with the same accurate real-time information. For instance, some travelers may comply to the presented information with trust, or others simply do not. In another example, their value of travel time against cost can also vary, and thus the monetary incentives affect travelers very differently. The choice heterogeneity has not been fully incorporated into the optimal traffic routing. Mahmassani and Liu (1999) showed that trip makers have different departure time and route switching behavior with real-time traffic information provision. For instance, older commuters tolerate greater schedule delay than younger commuters, and real-time information provision can incur greater frequency of route switching. Other studies, including Mahmassani and Jayakrishnan (1991) and Jayakrishnan et al. (1994), provided modeling frameworks and evaluation tools to analyze the effect of real-time information provision on congested traffic network. In our study, the heterogeneity of travelers is explicitly modeled via the value of time (VOT) distributions or the compliance rate of travelers to routing advice.

The second issue is regarding uncertain demand. Travelers tend to make their route choices following their day-to-day traveling experience, which may lead to the user-equilibrium (UE) network flow (Wardrop, 1953). UE works with deterministic demand and assumes stabilized route choices, both of which do not generally hold for the purpose of real-time traffic routing at the level of minutes. Demand variation, from time to time, a critical feature of demand uncertainty, can significantly change the traffic condition and bring inefficiency to the network. Do Chung et al. (2012) and Gardner et al. (2008) pointed out demand uncertainty is significant when considering congestion and congestion pricing of road networks, as well as the performance of the traffic systems (Waller et al., 2001). The congestion duration and pattern can vary substantially with an incremental change of travel demand presented by Qian and Michael (2011). We explicitly include the demand uncertainty into our model by regarding the traveling demand as random variables.

In this paper, we develop a stochastic control approach for real-time sensing and traffic routing that leads to system optimum. The model is generic in the sense that the optimal routing strategies can be achieved through various techniques, such as connected vehicle communications, navigation systems, and dynamic message signs, just to name a few. We specifically consider the demand uncertainty and choice heterogeneity in the problem. This system optimum minimizes the total expected travel time of all travelers. Solely depending on the real-time sensing, the controller optimizes the portion of travelers that will be fed with the suggested routes in the real time. For a symbolic two-route corridor network, a concise and insightful optimal routing solution is mathematically derived. The optimal policy is tested in numerical experiments to ensure its performance and efficiency. Furthermore, various traffic control applications in real road networks for implementing this optimal routing strategy are studied and discussed.

The main contribution of this paper is summarized as follows:

- (i) This research derives the analytical solution to real-time system optimal traffic routing of a two-route network considering demand uncertainty. Distinct from traditional system-optimum dynamic traffic assignment (SO-DTA)

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