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Dynamic traffic routing in a network with adaptive signal control

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ABSTRACT

In real traffic networks, travellers' route choice is affected by traffic control strategies. In this research, we capture the interaction between travellers' route choice and traffic signal control in a coherent framework. For travellers' route choice, a VANET (Vehicular Ad hoc NETwork) is considered, where travellers have access to the real-time traffic information through V2V/V2I (Vehicle to Vehicle/Vehicle to Infrastructure) infrastructures and make route choice decisions at each intersection using hyper-path trees. We test our algorithm and control strategy by simulation in OmNet++ (A network communication simulator) and SUMO (Simulation of Urban MObility) under several scenarios. The simulation results show that with the proposed dynamic routing, the overall travel cost significantly decreases. It is also shown that the proposed adaptive signal control reduces the average delay effectively, as well as reduces the fluctuation of the average speed within the whole network.

1. Introduction

Regular vehicles like the ones most of us are driving today don't have real-time road traffic information. The routing strategies used are either based on past experience or based on limited local information. This leads to the fact that regular vehicles can't respond to road incidents in a timely manner to avoid long delay. However, with the emergence of connected vehicles technology it is possible to access both local and global real-time traffic information via the V2X infrastructure. It is an important and challenging research problem to study how to take advantage of the extraordinarily rich information we can get from the connect vehicle system. The main objective of this paper is to study the interaction between two major components: dynamic vehicle routing and adaptive traffic signal control in a connected vehicle environment. We consider different combinations of route choice strategies and various traffic signal control methods to obtain an effective joint vehicle routing and signal control scheme which will reduce the average travel time within the network.

Vehicle routing problems have been very well studied over the years. A great part of the existing papers studies how to route vehicles in a network efficiently to meet some constraints like location routing (Perl and Daskin, 1985; Min et al., 1998; Nagy and Salhi, 2007) or time constrained routing (Desrosiers et al., 1984, 1995; Solomon and Desrosiers, 1988; Nie and Wu, 2009). The routing problem in this paper is focused particularly on how to route vehicles in the network so that the total time

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for the vehicles to get to their destinations can be minimized. The underlying problem for that is the well-known shortest path problem (SPP).

In the study of shortest path problem, the existing work can be categorized in two main groups: deterministic shortest path problem (DSPP) and stochastic shortest path problem (SSPP). Bellman (1956) proposed a dynamic programming method to solve the optimal route from one point to another with all link travel time to be deterministic and known ahead of time. SSPP is more interesting than DSPP as in real word link cost is usually not known deterministically but has many uncertainties. In stochastic scenarios, the shortest path problem can be further categorized into two groups according to Gao and Chabini (2006): path problem and optimal routing policy problem. Path problem aims to find a specific path (a deterministic link set) to destination that will attain a certain objective, such as least expected travel time (Miller-Hooks and Mahmassani, 2000) or maximum on-time arrival probability (Fan et al., 2005). Optimal routing policy problem, however, is more complicated than the path problem. According to Gao and Chabini (2006), a routing policy is defined as a decision rule that specifies which node to take next at each decision node based on realized link travel times and the current time. Compared with path problem, optimal routing policy problem in most cases can give a routing solution that is more efficient and reliable. The reason for that is because as the traveller travels in the network, he gains knowledge of the network (in this example, the travel time experienced after the traveller traverses a link). With this knowledge and the dependency of links being known, his anticipation of the future can be changed. The traditional path finding method does not take advantage of the newly learned information and the dependency between links. In order to take these advantages to improve the routing decision, the aforementioned optimal routing policy is needed. The optimal routing policy will not give one fixed path but a decision tree that will guide the traveller to the next node based on the current state(in most of the cases it is the arrival time at the current node) at the decision node. The optimal routing policy is particularly useful in stochastic and time-dependent networks. This routing policy is sometime known as hyper-path in some literature. Miller-Hooks and Mahmassani (2000) studied the least expected travel time problem using hyper-path algorithm in a stochastic and time-varying network. Fu (2001) also studied an adaptive routing approach with real-time information. Chen and Nie (2015) studied the stochastic optimal routing problem for vehicles with a limited travelling limit. The problem is formulated as a two-stage stochastic shortest path problem: both stages are a stochastic shortest path problem respectively. A label correcting based algorithm is used to solve the problem. However, their model does not consider time-variant link cost. Wu (2015) studied the travel reliability as an extension to the traditional shortest path problem in stochastic and time-dependent networks by adding the standard deviation to the mean travel time to represent the reliability of a certain route. However, the work does not explicitly consider the time-dependent problem in their formulation.

For signal control, most of the existing papers do not consider the interaction with traffic routing. The traditional control method, no matter adaptive or fixed-time, isolated or coordinated, only aims to reduce the delay or maximize the throughput of the intersection with known and perhaps time-dependent traffic demand (Rosdolsky, 1973; Hunt et al., 1982; Lo, 1999; Mirchandani and Head, 2001; Choy et al., 2003; Tatomir and Rothkrantz, 2004; Cheng et al., 2006; Haddad et al., 2013). This in reality might cause inefficient traffic routing, as traffic may oscillate between different routes due to the impact on travel delay caused by the signal control. Vehicles may make unnecessary reroute to avoid a red light at a certain intersection: for example when they see a red signal for the through movement, they may change their route and take a right turn in order not to wait at that intersection. This myopic behavior not necessarily guarantees to reduce the total travel time as the traveler may experience more red light stops (more delay) at the downstream intersections. It also causes fluctuations of road traffic as travelers are switching their routes too frequently. The fluctuation of road traffic has many negative effects on traffic control (Horowitz, 1984; Friesz, 1985; Zhang and Nagurney, 1996). So a good signal control strategy should take the interaction with vehicle routing behavior into consideration to achieve a better overall performance: not only reducing average travel time, but also maintaining a relatively stable on-road traffic. It requires the work to integrate traffic routing together with signal control. The problem is no longer a simple shortest path problem but a more complicated time-constrained shortest path problem (TCSPP).

In early literature, there have been many papers trying to solve the combined traffic assignment and traffic control problems, known as CTAC. Smith and Ghali (1990) studied the dynamics of traffic assignment and traffic control. When demand was constant, they were able to get a steady (equilibrium) state, but for dynamic demand they were unable to obtain such results. Later on, Yang and Yagar (1995) formulated the CTAC problem in a bi-level programming formulation. The upper level tried to minimize the system cost by varying the signal settings while the lower level modeled travellers' routing behavior which will give an equilibrium flow state given the signal settings. They also proposed an efficient method to solve the bi-level optimization problem. All the aforementioned papers were focusing on static networks. In reality traffic flows are varying from time-to-time and from day-to-day. A more sophisticated model should be used in order to solve the real world problem. Xiao and Lo (2014) formulated a joint dynamical traffic system that considered both travellers' route choices and traffic light control. The dynamical system permitted the signal controller to interact with and adapt to route choices of travellers, and vice versa in a day-to-day setting. Zaidi et al. (2015) applied the back-pressure algorithms from communication networks to the traffic network with adaptively re-routing traffic.

The aforementioned papers that jointly consider traffic assignment and signal control are all path based, and most of them consider static user equilibrium rather than adaptive control, which means they are unable to provide real-time routing guidance to individual travellers. In real world applications, it is more useful and has more significant impact to travellers if a system can offer good routing guidance at an individual level. This brings attention to combined traffic routing and signal control. Chen and Yang (2000) studied the shortest path problem in traffic-light networks. The constraints in their work were