Transportation Research Part B 67 (2014) 1–17

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Distributed coordinated in-vehicle online routing using mixed-strategy congestion game

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ARTICLE INFO

Article history:
Received 25 November 2013
Received in revised form 4 May 2014
Accepted 5 May 2014

Keywords:
Online coordinated in-vehicle routing guidance
Routing game
Distributed algorithm
Discrete choice model

ABSTRACT

This study proposes a coordinated online in-vehicle routing mechanism for smart vehicles with real-time information exchange and portable computation capabilities. The proposed coordinated routing mechanism incorporates a discrete choice model to account for drivers' behavior, and is implemented by a simultaneously-updating distributed algorithm. This study shows the existence of an equilibrium coordinated routing decision for the mixed-strategy routing game and the convergence of the distributed algorithm to the equilibrium routing decision, assuming individual smart vehicles are selfish players seeking to minimize their own travel time. Numerical experiments conducted based on Sioux Falls city network indicate that the proposed distributed algorithm converges quickly under different smart vehicle penetrations, thus it possesses a great potential for online applications. Moreover, the proposed coordinated routing mechanism outperforms traditional independent selfish-routing mechanism; it reduces travel time for both overall system and individual vehicles, which represents the core idea of Intelligent Transportation Systems (ITS).

1. Introduction and motivation

Recent years, wireless communication, on-board computation facilities (personal digital assistants, smart phones, etc.) and advanced sensor techniques (loop detector, camera, GPS-based vehicle probe, etc.) have been integrated into transportation systems. These new technologies establish information exchange in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) networks, and further enable real-time traffic information to be collected, processed, and disseminated among smart vehicles, road infrastructure, as well as traffic management centers. Accordingly, a type of well-connected and information-rich transportation systems, connected vehicle system (CVS), is under rapid development and is expected to be fully implemented in the near future. It enables us to create distributed but coordinated traffic applications to improve mobility, safety, environmental friendliness of transportation systems.

The proposed research is particularly interested in improving traffic mobility through CVS technology. We notice that CVS has prompted many advanced in-vehicle routing guidance systems embedded with a priori or en-route algorithms (Papageorgiou, 1990; Ben-Akiva et al., 1996; Jahn et al., 2005; Kaufman et al., 1991; Kaysi et al., 1993). Some of them have been implemented by pioneer practitioners, such as Waze, a community-based traffic and navigation app developed by

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http://dx.doi.org/10.1016/j.trb.2014.05.003
0191-2615/

Israeli start-up Waze Mobile. These routing guidance systems seek to intelligently guide individual travelers to avoid traffic congestion (Kim et al., 2005; Fu, 2001; Miller-Hooks, 2001; Miller-Hooks and Mahmassani, 2000; Pretolani, 2000; Kaufman et al., 1991; Du et al., 2013), taking advantage of the real-time traffic information provided to individual smart vehicles.

Even though CVS has been granted a great potential to intelligently route travelers (smart vehicles), scholars have recognized that if each smart vehicle independently chooses the shortest path based on uniformly shared real-time traffic information, it may only be beneficial when smart vehicles are the minority and their route choices do not impact traffic flow significantly. Smart vehicles may take advantages of the real-time information and find shorter paths which non-smart vehicles may not be able to recognized. However, as smart vehicles become the majority (which is expected as the related technologies are improved further), their route choices will impact traffic flow significantly. Then, current uniform real-time information provision may lead to even worsen traffic congestion, given each smart vehicle still selfishly and independently chooses its own shortest paths. For example, many smart vehicles sharing uniform information are very likely to choose a same link/corridor not crowed at the time that route choices are made, and then it becomes highly congested when they arrive at the link/corridor.

This inherent deficiency of current routing methods with uniform real-time provision is rooted from the inconsistency between system performance (system-optimality) and individual vehicles' route choice behavior (user-optimality). As different strategies are used to treat this inconsistency, various routing mechanisms can be developed. This study considers most of current in-vehicle routing mechanisms as independent selfish-routing mechanism (IRM), which gives the priority of the routing to user-optimality and leaves system performance out of control or under very limited control. As we mentioned before, IRM may cause system congestion when adopted by majority of the traffic flow. Accordingly, individual users also lose the benefit of using it. On the other hand, if the priority of routing mechanism is given to system-optimality, pure systematical optimal routing mechanisms (SRM) can be developed, which sacrifice some vehicles' travel time to achieve system optimality (i.e. smart vehicles are fully cooperated). SRM overwhelms the need of user-optimality and certainly conflicts the selfish nature of vehicles' route choice behavior, thus cannot work well in practice. The above observation indicates a need of new routing strategies/mechanisms which enable proper coordinations among vehicles (i.e. individual vehicles and traffic system) so that both the overall system and individual vehicles benefit from the provision of real-time traffic information. Recent advances of CVS have sustained the technique feasibility to develop this kind of coordination among smart vehicles, and to implement coordinated routing mechanisms.

Motivated by the above views, the proposed study seeks to develop a novel coordinated online in-vehicle routing mechanism (CRM) based upon routing game theory and distributed algorithm technique. The proposed CRM aims to artfully overcome the deficiency of traditional IRM without violating selfish natural of route choice behavior. Under this mechanism, we consider a trip of a smart vehicle from its origin to destination as a constant information exchange and multiple route choice decision process. Namely, during a trip, each individual vehicle keeps collecting and disseminating traffic information including its preference on the route options. As the trip is close to each intersection, a smart vehicle joins an online routing coordination group and decides route choice in candidate route options. The coordination group is dynamically formed by the vehicles that are close to an intersection and/or about to make routing decisions in the traffic network under consideration. The priorities of its candidate route options (route choice probability distributions) are identified by near future traffic condition revealed by recent traffic condition and route choices of all other smart vehicles in the coordination group. In an online routing coordination group, each smart vehicle iteratively proposes and updates its routing choice priorities, responding to real-time traffic information (incorporating their most recent route choices) based on exchanging information with other smart vehicles through an online communication environment; the negotiation process ends with a resolution (represents an equilibrium route choice decision) among all smart vehicles, which leads to the final route choice of smart vehicles. The proposed mechanism guarantees the optimality of individual vehicle's route choice priorities (given others in the group do not deviate from their priorities). And as will be shown in the experiments, this mechanism will also lead to much better overall system performance compared to pure selfish-routing without coordination.

The proposed mechanism has four distinguished technical characteristics. (i) The proposed routing mechanism can be regarded as an adaptive online routing process. Smart vehicles re-decide route choices at each intersection according to real-time traffic information. (ii) The routing mechanism relies on information sharing. Hence, a virtual online routing coordination group and an underlying supporting communication platform are needed. They are enabled by V2V and V2I networks in CVS. The privacy issues associated with this information sharing can be solved by privacy protection algorithms such as Jung et al. (2013). (iii) The routing decision of each vehicle is the priorities of the candidate route options, which is represented by a probability distribution. The combination of traffic information sharing and routing decision is reflected by modeling the route decision making process as a mixed strategy routing game. The equilibrium routing decision represents user-optimal route decision for each individual vehicle. (iv) The coordinated routing mechanism is proposed to be implemented in a distributed fashion by employing the in-vehicle computation resources. It implies that each vehicle will carry out the computation locally and a super powerful central control unit is not needed. In short, the aforementioned characteristics indicate that the proposed routing mechanism belongs to adaptive distributed online routing strategy; each routing decision making procedure is modeled as a mixed strategy atomic routing game; and it is proposed to be distributively implemented. Even though this proposed routing mechanism is initiated by the case of high smart vehicle penetrations and it shows more value to be applied under this condition, this study will also demonstrate that it works reasonably well