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Coordinated online in-vehicle routing balancing user optimality and system optimality through information perturbation

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A B S T R A C T

The inconsistence between system optimality and user optimality represents one of the key difficulties on network traffic congestion control. The advanced connected vehicle systems, enabling smart vehicles to possess/exchange real-time information and conduct portable computation, provide new opportunities to address this challenge. Motivated by this view, this study proposes a coordinated online in-vehicle routing mechanism with intentional information provision perturbation (CRM-IP), which seeks to shape individual vehicles online routing decisions so that user optimality and system optimality are balanced, by exploiting bounded rationality of the users. The proposed CRM-IP is modeled as a pure strategy atomic routing game, and implemented by a sequentially updating distributed algorithm. The mathematical analysis is conducted to quantify the absolute gain of system optimality corresponding to the loss of user optimality resulting from a given level of the information perturbation in the worst case so that the efficiency of the information perturbation can be evaluated. Furthermore, numerical experiments conducted based on City of Sioux Falls network investigate the average effects of the CRM-IP on system optimality and user optimality under various network traffic conditions, comparing to the CRM developed by Du et al. (in press). The results indicate that the improvement of system optimality and the reduction of individual vehicles' travel time from the CRM is more significant when the network traffic is under an mild congestion state, such as under the levels of service (LOS's) C, D, and E, rather than under extremely sparse or congested states, such as under LOS's A and B, or F. Moreover, higher level of information perturbation benefits system optimality more, but the marginal effect decreases after the perturbation reaching certain level, such as $\lambda = 0.1$ in this case study. In addition, a portion of vehicles may sacrifice user optimality due to the information perturbation, but the extent of the sacrifice is not significant, even though it increases with the information perturbation level. Hence, a small information perturbation is recommended to achieve an efficient network traffic control through the CRM-IP. Overall, this study proposes the CRM-IP as an efficient routing mechanism, which has a great potential to guide the routing decisions of individual vehicles so that their collective behavior improve network performance in both system optimality and user optimality.

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1. Introduction and motivation

Connected vehicle systems (CVS's) including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) information exchange have a great potential to address main challenges in current transportation systems such as traffic safety, mobility, as well as environmental relevant issues, and thus have attracted significant attention from both academia and industry. What interests this study most is that CVS's provide individual drivers the access to real-time traffic information as well as the mobility information of neighborhood vehicles, which enables two critical capabilities: (1) Individual vehicles may perform adaptive and intelligent route choice decision en-route to avoid traffic congestion. (2) Traffic controller may perform traffic congestion control through strategic information provision, which affects individual vehicles' route decisions to approach desired system performance. Namely, if proper route guidance combined with strategic information provision is provided, we expect that both system and individual vehicles will benefit from traffic congestion management, given vehicles still perform selfish and self-directed route choices.

Motivated by the above features, Du et al. (in press) proposed a coordinated routing mechanism (CRM) that allows smart vehicles to "negotiate" with each other when they make online routing decisions enroute, so that potential traffic congestion in the near future can be avoid to some extent. Even though the experiment results indicates the CRM leads to significant improvement of system performance compared to the traditional independent routing mechanism (IRM),[1] this study noticed that the CRM does not explicitly sustain system optimality (i.e., minimizing system total travel time) and only considers user optimality (i.e., no smart vehicles can benefit from deviating from an equilibrium joint routing decision; note that user(s) and vehicle(s) are exchangeable throughout the paper). It is well known that user optimality is crucial to ensure the complying of a routing guidance, but improving system performance is the ultimate gaol of a transportation congestion management. Unfortunately, user optimality and system optimality do not coincide most of the time in reality. This fact represents one of the key challenges for efficient traffic congestion management. At the mean time, recent studies of bounded rationality of the travelers (i.e., a small difference of the travel cost is usually not perceived) indicate that it is affordable to compromise user optimality to some extent in exchange for improved system performance.

Inspired by the above views, this study moves forward from Du et al. (in press) and develops a coordinated online in-vehicle routing mechanism with information perturbation (CRM-IP), which balances user optimality and system optimality under the framework of the CRM by intentionally perturbing information provision. More specifically, this mechanism is built upon a system composed by the following items: (1) Smart vehicles which are about to make route choices forms a routing coordination group. Each smart vehicle here is willing to share traffic information including its (tentative) route choice; and (2) an information center that collects, processes, and dissimulates real-time information including general traffic condition, vehicles' tentative route choice, and travel time prediction among smart vehicles. The routing decision making process following the CRM-IP is described as follows. Smart vehicles in the coordination group propose their tentative route choices according to predicted route travel time provided by the information center, and then inform the information center their tentative route choices. The information center collects the tentative route choices, predicts the travel time, performs a strategic perturbation and then disseminates to smart vehicles. Next, the smart vehicles again propose their tentative route choices according to the newly predicted travel time. This process continues until no vehicles have the incentive to change their routes.

This study models the CRM-IP as a pure strategy,[2] atomic routing game possessing an equilibrium joint routing decision, which can be searched by a designed sequentially updating distributed algorithm (SUDA (Du et al., in press)). Both theoretical analyses and numerical experiments in this study prove that the proposed CRM-IP leads to a joint routing decision, for which the relative loss in user optimality (will be made precision later in the paper) can be bounded from **above** by how much perturbation is added; more importantly, the absolute gain in system performance can be bounded from **below** in terms of the absolute loss in user optimality. The main contributions of the paper are highlighted by: (i) proposing a coordinated online in-vehicle routing mechanism with information perturbation based on game theory; (ii) Rigourously bounding user optimality loss and system optimality improvement in terms of information perturbation level; and (iii) Conducting numerical experiments to demonstrate the effects of information perturbation on both user optimality and system optimality under the CRM-IP routing mechanism.

The rest of the paper is organized as follows. Section 2 reviews the existing relevant studies. Sections 3 and 4 together develop the CRM-IP by introducing the CRM and developing information provision strategy respectively. Mathematical analyses on the effects of this perturbation on system optimality and user optimality are also provided in Section 4. Further, Section 5 presents a distributed algorithm to search a joint routing decision of smart vehicles following the CRM-IP. Section 6 conducts numerical experiments to investigate the average performance of the CRM-IP; insights and discussions based on the experiment results are included. Section 7 concludes the paper.

[1] smart vehicles make best reaction according to the real-time information independently without coordination.

[2] This game is called a pure strategy game since the vehicles' strategy set is composed of individual paths instead of the probability distributions on the paths.