# Heterogeneous Information Provision on Traffic Networks with Competitive or Cooperative Information Providers

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## 1 Introduction

In recent years, many GPS-based route navigation systems, such as Waze and Google Maps, arise in traffic networks. For a given origin-destination (OD) pair, these systems recommend travelers alternative route choices with estimated travel times and out-of-pocket costs. In traffic networks with multiple information provides (IP), the information provided by different IPs is generally non-identical due to technological differences. It contributes to an inherently heterogeneous information structure among the travelers' population since travelers rely on different IPs. Moreover, IPs may play either competitively or cooperatively to maximize their respective profits. Therefore, it is necessary to consider information heterogeneity resulting from multiple IPs with various competition or cooperation strategies.

There are two streams of relevant literature. The first stream focuses on the effects of heterogeneous information on travelers' behavior and travel cost. Several studies investigate information heterogeneity using Bayesian congestion games (Liu et al., 2016; Wu et al., 2017, 2018). They consider that different Traveler Information Systems (TIS) provide information about traffic incidents with different accuracy levels. Khan and Amin (2018) adopt the Bayesian framework to study the effects of asymmetric information on Vickrey (1969) 's bottleneck network. From a different perspective, Acemoglu et al. (2018) introduce a new class of congestion game in which users have different information sets about the available edges and can only use routes consisting of edges in their information set. The second stream studies the strategic interactions of information service providers. A competitive routing problem with multiple navigation providers has been investigated (Zakharov and Krylatov, 2014, 2016; Krylatov et al., 2016). They investigate the Nash game and the cooperation of navigation providers. However, they ignore users' behavior by assuming users behave following the System Optimum (SO). Moreover, these studies are conducted on single-OD networks with parallel routes, which limits the application of their results.

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Despite the significant body of work on the effects of information provision, to the best of our knowledge, there is no study considering both the strategic decisions of IPs and users' route choices. This paper addresses this gap and investigates the long-term effects of information provision on traffic networks with multiple IPs. We develop three models to investigate IPs' strategic decisions in the three situations: Nash game, Stackelberg competition, and cooperation. For the Nash game model, we explore the impacts of unit information cost and the market share distribution on IPs' information set decisions, IPs' profits, and system-wide congestion. Moreover, the results are compared with that in the cooperation model. For the Stackelberg competition model, we investigate the leader and the follower's decisions, their profits, and the system performance. Information paradox is also examined.

## 2 Methodology

We consider that IPs offer route guidance services for free. Each IP aims to maximize its profit, which is the difference between the revenue and the cost. An IP's revenue comes from advertising and monetizing users' data through related channels (Google, 2016; Waze, 2016). The cost consists of the cost of information provision and the cost of total travel time of its users. It is assumed that users subscribe to different IPs, which provide non-identical information sets about the available routes. Therefore, a user can only choose a path from the information set provided by her subscribed IP. The Wardrop Equilibrium with Multiple Information Classes (WEMIC) is introduced to describe users' behavior in this context, which is a generalized version of Wardrop equilibrium. In WEMIC, users choose routes with minimum cost among paths in their respective information set.

The problem can be formulated as a leader-follower game. At the lower level, travelers are followers who make route choices based on their information sets following the principle of WEMIC. At the upper level, IPs are leaders who competitively or cooperatively determine the information sets provided for their users to maximize their profits. We develop three models to investigate IPs' different strategic behaviors: Nash game, Stackelberg competition, and cooperation.

We first propose a model in which IPs play a Nash game at the upper level, the problem is formulated as an EPEC (Equilibrium Problem with Equilibrium Constraints), in which the WEMIC conditions are formulated as equivalent variational inequalities (VI).

The second model captures the Stackelberg competition among IPs with one IP acts as the leader and other IPs behave as followers. The problem is formulated as a bi-level program. The upper level describes the leader's decision, whereas followers play a Nash game subject to WEMIC conditions at the lower level. When multiple Nash equilibria among followers arise, we consider the pessimistic case. That is, the followers will end up playing an equilibrium that minimizes the leader's payoff.

In the cooperation model, IPs cooperatively determine information sets for each involved IP to maximize the total profit. An IP's profit in cooperation is adjusted to better capture the characteristics of cooperation. We consider that IPs in the cooperation can share user data to improve the quality of crowdsourcing data and share path information to reduce the cost of information provision. The problem is to maximize the total modified profit subject to WEMIC conditions.

## 3 Results

We propose a Nash-dominance based evolutionary algorithm. to solve the proposed EPEC efficiently. To improve computational efficiency, a heuristic method based on the k-shortest path routing algorithm is proposed to reduce IPs' action space. Numerical experiments are conducted on a five-link network and the Nguyen Dupuis (1984) network. Two information providers are considered; one with a larger market share represents the big company, the other with a smaller market share represents the small company.

In the five-link network, we find that in the Nash competition, the small company (IP 1) may be better off with the increase of unit information cost (i.e., $\lambda$) while the big company (IP 2) suffers profit loss (see Fig.1). As shown in Fig.2, generally, high unit information costs deteriorate the system congestion. However, system-wide congestion is not minimized at the lowest unit information cost. Fig.3 compares the profit and users' total travel time (TST) in Nash competition and cooperation. It shows that both IPs gain no less profit in cooperation, and the small company gains more profit from cooperation than the big company. Overall, the system-wide congestion and the impact of IPs' strategic behavior on it are minimized when the unit information cost is within a moderate range.

In the Stackelberg competition with the big company being the leader, we demonstrate that the leader losses profit but the follower gain profit with the leader expanding its information set. The system performance is improved with the leader's information set expansion, but it is not optimized under the full information set. Moreover, IPs gain more profit and the system travel time is lower with lower congestion degrees. Nevertheless, when the leader provides a small information set, a higher congestion degree may direct users away from the path with high externality so that system-wide congestion is alleviated.

In the Nguyen Dupuis(ND) network, the IP with increasing market share gains more profit in the Nash competition. Given a fixed total number of users, the market share distribution between IPs does not exert an evident influence on the system travel time. It reveals that the competition between IPs is beneficial for maintaining a steady system performance in the long run. We also evaluate the performance of the proposed algorithm on the ND network. After reducing IPs' action space, on average, the number of iterations requires to converge drops from 107 to 56, and the computational time is reduced by almost half. At convergence, the standard deviations of the population of profits are all less than 0.0001.

## 4 Conclusions

This paper systematically analyzes the effects of heterogeneous information provision in traffic networks with multiple information providers. Our models capture the strategic interactions among IPs, user's route choice, and the interaction between IPs and users. We investigate the impact of unit information cost, congestion degree, and market share distribution on the information provision process and results. Based on the results, we provide insights from both the perspectives of system and IPs. This paper's limitation is that we consider IPs' behavior in either fully competitive or fully cooperative scenarios. It is more realistic to consider that both cooperation and competition co-exist in the market.

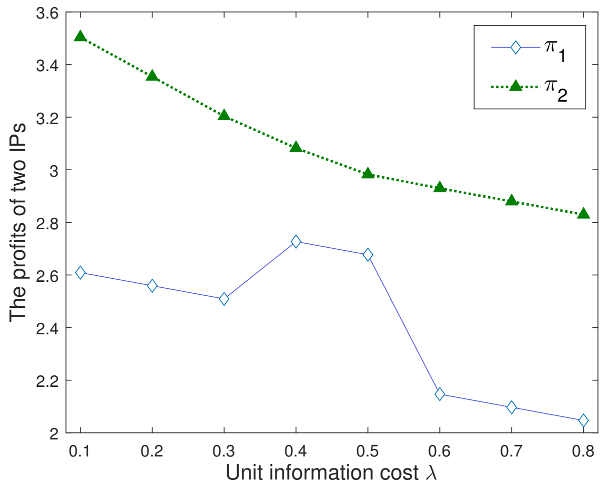


Figure 1: The profit of two IPs

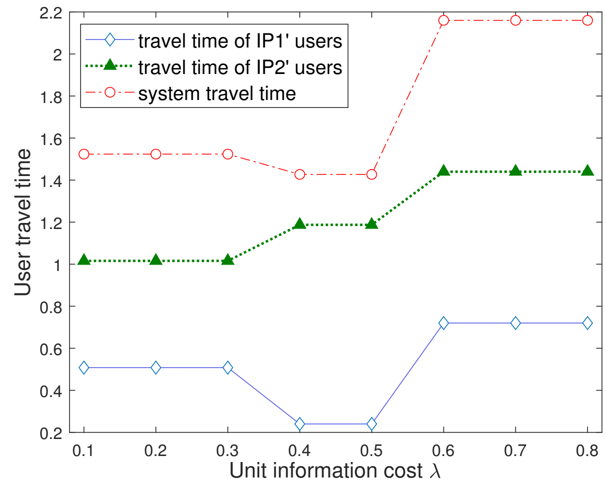


Figure 2: Users' travel time

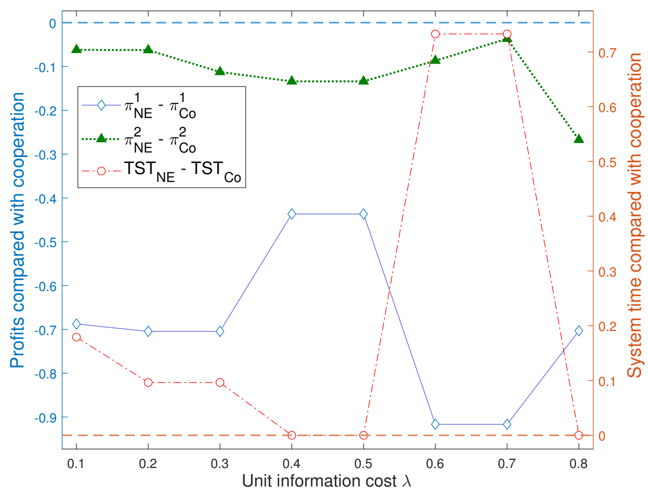


Figure 3: The profit and system time gain/loss in Nash competition compared with cooperation

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## References

Liu, J., S. Amin, and G. Schwartz, Effects of information heterogeneity in Bayesian routing games. *arXiv preprint arXiv:1603.08853*, 2016.

Wu, M., J. Liu, and S. Amin, Informational aspects in a class of bayesian congestion games. In *2017 American Control Conference (ACC)*, IEEE, 2017, pp. 3650–3657.

Wu, M., S. Amin, and A. E. Ozdaglar, Value of Information in Bayesian Routing Games. *arXiv preprint arXiv:1808.10590*, 2018.

Khan, Z. and S. Amin, Bottleneck model with heterogeneous information. *Transportation Research Part B: Methodological*, Vol. 112, 2018, pp. 157–190.

Vickrey, W. S., Congestion theory and transport investment. *The American Economic Review*, Vol. 59, No. 2, 1969, pp. 251–260.

Acemoglu, D., A. Makhdoumi, A. Malekian, and A. Ozdaglar, Informational Braess' paradox: The effect of information on traffic congestion. *Operations Research*, Vol. 66, No. 4, 2018, pp. 893–917.

Zakharov, V. and A. Krylatov, Equilibrium assignments in competitive and cooperative traffic flow routing. In *Working Conference on Virtual Enterprises*, Springer, 2014, pp. 641–648.

Zakharov, V. V. and A. Y. Krylatov, Competitive routing of traffic flows by navigation providers. *Automation and Remote Control*, Vol. 77, No. 1, 2016, pp. 179–189.

Krylatov, A. Y., V. V. Zakharov, and I. G. Malygin, Competitive traffic assignment in road networks. *Transport and Telecommunication Journal*, Vol. 17, No. 3, 2016, pp. 212–221.

Google, About local search ads on Google Maps, 2016.

Waze, Advertise With Waze, 2016.

Nguyen, S. and C. Dupuis, An efficient method for computing traffic equilibria in networks with asymmetric transportation costs. *Transportation Science*, Vol. 18, No. 2, 1984, pp. 185–202.