Information-Theoretic Decision-Making for Multiple Agents in Uncertain Network Conditions

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For transportation networks under high uncertainty, an information-theoretic decision-making framework helps agents choose routes that maximize the mutual information gain for unexplored locations while minimizing exploration cost. In post-disaster environments, damage to the transportation sensor network causes non-recurring uncertainty in link traversability or travel time for autonomous vehicles (AVs) attempting to assist victims. Normally functioning transportation networks under stochastic dynamic demands due to heterogeneous driver behavior present recurring travel time uncertainty. This research considers two scenarios in which link travel times are uncertain. First, routing AVs in a post-disaster grid-based scenario with environmental correlation and non-recurring travel time uncertainty. Second, information-theoretic dynamic traffic assignment for a congested transportation network scenario under recurring uncertainty in which a fraction of vehicles are connected vehicles driven by humans.

Human decision making based on travel time reliability has been extensively studied [2, 6], but the prediction of travel time and link speed depends on traffic sensors and other infrastructure [5]. Prior research considering "informed" drivers does not consider quantifying information gain [3]. Instead, "information" refers to agents sending or receiving updates from the system. The fraction of vehicles sharing information has been demonstrated to affect the stability of a transportation system [3].

Multi-agent information sharing approaches for solving routing and scheduling problems have been successful in recent years [7]. Entropy constrained mixture distributions based on current network conditions and future predictions using agent decisions are effective in reaching a network equilibrium condition [1], but a mixture distribution between route travel time and a utility function was not considered. Dynamic toll pricing has also been used to explore bounded rationality user equilibrium flow patterns [4], however, the effect of disinformation has not been addressed.

The first case study considers multiple AVs on an uncapacitated network in a simulated disaster area. An anticipatory path planning methodology is presented for AVs to consider the spatiotemporal correlation between locations. In a correlated environment with uncertainty, the cost of visiting

any location is balanced by the benefit of gaining information about other locations. This case study presents a utility-based multi-agent framework for routing AVs through regions of high uncertainty, as shown in Equation 1.

$$U^i_{p,t} = W^i_2 cost^i_{p,t} - W^i_1 \sum_{j \in p} \left[(SD_{j,prior} - SD_{j,posterior}) \right] \tag{1}$$

Building on the information-theoretic routing framework, the second case study is currently ongoing and considers travelers simulated on a capacitated road network. Unlike previous research, informed travelers do not receive perfect information. Travel time updates will be strategically altered using information theory to influence human driver decision making such that a fraction of informed travelers are encouraged to take detours and observe uncertain links. The information gained is then used to dynamically reroute other informed travelers toward the system optimal equilibrium. Using a mixture distribution of the route travel time and an information-theoretic utility function, subject to the constraint that information loss is minimized and the mean of the distribution lies outside the driver's indifference band, travelers are provided with sufficient disinformation to alter their route decision (Figure 1).

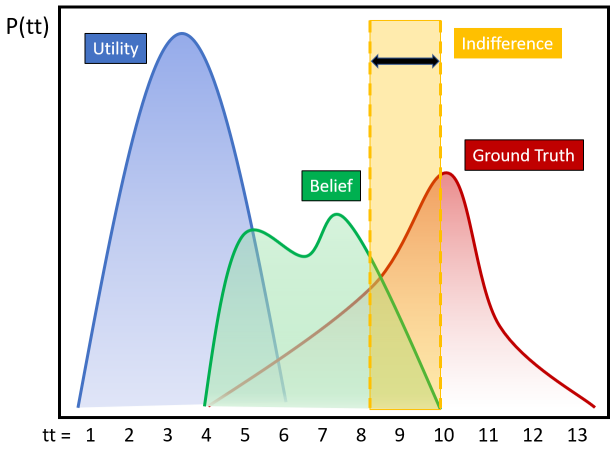


Figure 1 **A mixture distribution between the utility function and ground truth is used to generate a sufficiently disinformed travel time distribution to present the informed traveler.**

Using utility functions based on an information gain metric, the first case study presents the benefit of information-theoretic routing over myopic routing on a user defined grid. In a correlated environment with uncertainty, prioritizing information gain early in the trip allows a single agent to exploit the information gained over the rest of its trip. The benefit for a single AV is making more observations without exceeding the expected travel time. Information gain for a single AV was improved by up to 62% without exceeding the expected travel time. When multiple AVs are used, Monte Carlo simulations showed that the information gained results in a 7% reduction in travel time on average, and travel time reductions of up to 34% in ideal cases.

Results for the second case study will be presented using two examples. Figure 2a demonstrates that system optimal equilibrium can be achieved through the incorporation of strategic disinformation into a dynamic traffic assignment framework. Two possible routes exist for the Origin-



(a) Example Map 1 (b) Example Map 2

Figure 2 Example scenarios for Information-Theoretic Dynamic Traffic Assignment

Destination (OD) pair with each route having a unique travel time probability distribution. In addition to the ground truth information, travelers have their own perceived travel times which are based upon past experience and information about the current state of the two routes. For this example, all informed travelers choose Route A, while 50% of uninformed travelers take Routes A and B respectively. Through strategically misinforming a percentage of informed travelers such that they switch to Route B, the demand on Route A can be reduced sufficiently to prevent congestion.

The example in Figure 2b shows that observations can be made by misinformed source agents to improve travel time estimation and increase system performance. For travelers along the main route for the OD pair, there exists a possible detour to reach the destination which contains a link with high travel time uncertainty. Information from a source agent about the state of this link reduces the travel time uncertainty for routes containing this link.

This research offers a set of novel techniques for single and multi-agent path planning in uncertain environments. The use of an anticipatory path planning methodology considering spatiotemporal correlation ensures that the AV takes the fastest route based on updated information, or the route which maximizes information gain without exceeding expected travel time. This methodology provides improved routing in uncertain conditions, extending the range of the AV and providing more time for the AV to perform exploratory tasks in a disaster scenario. The same methodology is applicable to other scenarios involving the autonomous exploration of uncertain environments.

Additionally, a novel information-theoretic methodology for reaching system optimal equilibrium in normally functioning transportation networks will be presented. Using strategic disinformation, travelers are guided toward making decisions which help to explore the transportation network and

balance network load. This new methodology enhances system performance by reducing travel time uncertainty through network exploration and then exploits the information gained to dynamically assign optimal routes to informed travelers. Future work includes extending the model by combining strategic disinformation with incentive optimization.

Acknowledgments

Funding for this research was provided by the NSF RI #1910397, NASA JPL RSA #1625294, and NASA JPL Education office. Additional partial support was provided by the North Carolina Department of Transportation TAR 2019-09, Virginia Department of Transportation VTRC #116038, USDOT University Transportation Centers Contract 69A3551747125, and Chancellors Distinguished Fellows through the Department of Education Title III Program. The authors also express thanks to all reviewers of this extended abstract.

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