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Emergence of cooperation in congested road networks using ICT and future and emerging technologies: A game-based review

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ABSTRACT

Information and communications technologies (ICT) and future and emerging technologies (FET) are expected to revolutionize transportation in the next generation. Travelers' behavioral adaptation is a key to their success. We discuss the notion of managing traffic congestion by enhancing cooperation in road networks enabled with ICT and FET. Cooperation is an emergent social state related to the dynamics and complexity of road traffic and reinforced learning. Game theory and research in behavioral economics show that cooperation can be leveraged to efficiently solve social dilemmas similar to traffic congestion. We review the applicability of behavioral economics and game theory concepts to route, mode and departure time choice problems. Beyond advancing theory, research on cooperation in the context of transportation is still in its infancy. We discuss state-of-the-art methodologies and their weaknesses and review the unexplored opportunities inherent in game-based methodologies. A behavioral-technological research agenda for FET is also discussed.

1. Introduction

Future and emerging technologies (FET) are expected to revolutionize the ways people use vehicles and roads. The assimilation of ubiquitous computing capabilities and pervasive Information and Communication Technologies (ICT) into both the software and hardware of vehicles and transportation infrastructures introduces innovative opportunities to improve personal mobility, including a safer, more convenient, more efficient and greener travel experience (Spieser et al., 2014). Presently, ICT applications tackle congestion mainly with "software" developments intended to enable a better flow of information about traffic. Advanced Traveler Information Systems (ATIS) such as variable message signs (VMS) (Emmerink et al., 1996) and, more recently, real time mobile navigation applications (apps) such as Waze©, assist travelers in their spatial decision making, e.g., route, mode of travel, destination choice (Mokhtarian and Tal, 2013). These changes signal a move from an era in which travel information was experiential, obtained by trial and error, to an era of descriptive, and today prescriptive, travel information enabled via ICT mediums. Moreover, it is anticipated that the more the individual traveler benefits from such sources of information, the greater the aggregate benefit will be for the entire transport system.

This overwhelmingly positive outlook regarding the benefits that new technologies are expected to confer on travelers as a whole, however, is based foremost on critical assumptions about human travel behavior and how it is related to the behavior of the transport system, a relation characterized by high complexity. That is, the behavior of the whole is not

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simply extrapolated from the behavior of the individuals but rather, the two are linked in a co-evolutionary process. Although under perfect competition, supplying consumers with more information helps them maximize utility, the effect of incorporating more information in road networks is not straightforward. In fact, some studies showed that increased amounts of information can engender possibly adverse outcomes under both recurring and non-recurring (i.e., associated with random incidents or accidents) traffic congestion (Ben-Akiva et al., 1991; Emmerink et al., 1995a, 1995b; Lindsey et al., 2014; Lu et al., 2014).

The potential effects of information availability and accessibility can be examined from the perspective of the theoretical case of perfect information. Here the corresponding lack of uncertainty results in a stable traffic state known as User Equilibrium (UE) (Wardrop, 1952), whereby travelers have, by definition, perfect information on the state of the network and on the optional routes. It is also assumed that they behave rationally and selfishly, and thus, that they choose the near-state shortest path (in terms of time or generalized cost) between any given origin and destination. Similar to a Nash equilibrium (Nash, 1951), this state is stable, as it is unlikely that travelers will change their route choices given that they know that all other options are most likely worse. In heterogeneous and nonsymmetrical networks, UE is usually a suboptimal routing solution that reflects travelers' average travel costs. In contrast, the System Optimum (SO) is a secondary traffic state where the travel costs of all travelers combined are minimized, thereby reflecting their marginal travel costs. The gap between these two concepts can be quantified using the price of anarchy (Mak and Rapoport, 2013; Roughgarden, 2005).

The behavioral assumptions on which the UE prediction is based, i.e., rationality and selfishness, were borrowed from orthodox microeconomic theory. However, behavioral economists and psychologists alike, e.g., Simon (1982, 1955) and Kahneman and Tversky (1979), criticized those assumptions as poor representations of cognitive reality. In particular, behavioral economists question the extent to which selfishness is a determinant of behavior, citing the effects of other important behavioral traits such as other-regarding and social preferences (Bolton and Ockenfels, 2000; Fehr and Schmidt, 1999). While the mobility literature is aware of these critics of rationality (Avineri and Ben-Elia, 2015; Ben-Elia and Avineri, 2015a, 2015b) and has even recently discussed the importance of social influence (Abou-Zeid and Ben-Akiva, 2011), the issue of selfishness has been left practically untouched, as recently testified to by Daniel McFadden, regarded as the "forefather" of travel behavior modeling: "new results challenge the standard assumption of maximization of individualistic utility, indicating that social networks as information sources, reciprocity, and altruism enter human behavior and cannot be ignored" (McFadden, 2013, p. 37). People, among whom are the travelers, are not necessarily selfish Homo economicus, but instead can be understood as Homo sociologicus, a social animal (Hirsch et al., 1987).

Advances in ICT and expected developments in FET offer new opportunities that could promote the manifestation of unselfish behavior in road networks by introducing and enforcing the notion of travel behavior based on cooperation strategies. This could be done in conjunction with the deployment of Intelligent Transport Systems (ITS) and the associated vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) architectures. Indeed, it is anticipated that traffic congestion management efforts will eventually receive substantial support from ICT, particularly with the establishment of the Internet of Things (IoT or Internet 3.0) and technological breakthroughs in Connected Autonomous Vehicle (CAV) deployment. In the short run, CAVs will be able to communicate and exchange information via the IoT network, which will enable them to adopt routing strategies that will contribute to increased route reliability and decreased non-recurring congestion (incidents), perhaps ultimately transcending UE to attain SO network states. In the long run, a collectivized fleet of CAVs could be the foundation for the establishment of a demand responsive public transit system (e.g., Quadrifoglio et al., 2008) based on the mass uptake of ridesharing (e.g., Nourinejad and Roorda, 2015), a move that will generate wide savings in terms of reductions in cruising time for parking and in the time vehicles remain idle (Le Vine and Polak, 2015). More importantly, such a demand responsive system will provide travelers with a spatiotemporally relevant public transit system that is not necessarily fixed according to rigid routes or timetables. Furthermore, once CAVs are mobilized and effectively shared among the traveler population, the number of conventional vehicles in operation, as the principal generators of recurring congestion, could be significantly reduced (Fagnant and Kockelman, 2014; Spieser et al., 2014).

Although a CAV-dominated future has significant potential to solve many of our most pressing traffic problems, its success will depend foremost on whether travelers can be persuaded to learn to cooperate with each other. In the absence of cooperation, CAVs could instead become detrimental to traffic flow, as a recent simulation study demonstrated for a metropolitan-size transportation system in which carsharing practices (single driver with pooled vehicle fleet) crowded out public transit, leading to an increase instead of a decrease in traffic congestion (Martinez et al., 2015). Undoubtedly, much more research, in which the methodologies of existing theories are reconsidered, is required before these ideas can become part of everyday reality.

In this paper, we show how the combination of simple theoretical principles based on game theory, on the one hand, with emerging game-based methodological approaches, on the other, can create entirely new research avenues that will provide valuable insight into the cooperative nature of travel behavior and how this knowledge can be applied with FET to improve congestion management strategies. The rest of the paper is organized as follows. Section 2 presents the behavioral foundations of cooperation based on the theoretical literature from behavioral economics, game theory, and cognitive and social psychology. Section 3 examines strategies, including the use of ICT, for enforcing cooperation on road networks. In Section 4 we discuss research methodologies for evaluating the impacts of FET. Section 5 concludes this review paper and suggests a future research agenda for transportation researchers interested in the behavioral aspects of ICT and FET.