Emergence of cooperation and a fair system optimum in road networks: A game-theoretic and agent-based modelling approach

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ABSTRACT

Cooperation is an emergent social state related to the dynamics and complexity of road traffic and is reinforced through adaptive learning. Game theory and research in behavioural economics provide ample evidence that cooperation can efficiently solve social dilemmas similar to traffic congestion in dynamic settings. Traffic theory, asserts User Equilibrium, is both a stable and equitable, albeit inefficient, network state, which is a behavioural outcome of the selfish uncoordinated decision of drivers. In contrast, the System Optimum is an efficient network state that minimizes the total travel costs but is hard to maintain due to the inherent cost inequalities drivers will incur. In this paper, we describe how the principles of game-theory in a simple 2-player game allow the emergence of a stable system optimum through cooperation. We then investigate what happens in n-player games by applying an agent-based route-choice model. The model shows how reinforced learning and different behavioural specifications regarding agents’ cognition – selfish or cooperative - brings a simple road network from User Equilibrium towards the system optimum while preserving sufficient equity amongst drivers. The results suggest that a sufficient number of route alternations between drivers and a certain degree of altruism allow for a self-organizing formation of a fairness equilibrium that can maintain the network in the system optimum. The implications of future congestion management strategies that can be implemented with information and communication technologies are discussed.

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1. Introduction

Earth is becoming an urbanized planet. More than 53% of humanity (74% in Europe) lives in urban areas, and this figure will only increase, especially in developing and transitional economies (World Bank, 2013). People are attracted to cities because of the benefits of agglomeration and the access to a wide range of services and employment it brings. The growth in city populations, however, has been accompanied by a corresponding increase in traffic congestion, and as such, maintaining road traffic in smooth working order is becoming more difficult. Congestion is strongly related to the public good nature of transport infrastructure; lack of clear ownership rights and unclear price signals to users bring about overconsumption of transport services and overloading of existing capacities, in particular when commuting to and from work during rush hours. Cars maintain a significant symbolic and affective value (Steg, 2005), while public transport often fails to be an attractive transport alternative, as it is not able to provide services to anyone anywhere and anytime within acceptable operational and financial thresholds. Consequently, most people still choose to use the car for everyday mobility needs (Handy, Weston, & Mokhtarian, 2005) with the collective outcome being recurring congestion. Although congestion is a by-product of urban vitality, it also incurs negative externalities, such as time loss and delays, air pollution, noise, and decreasing safety (Mayeres, Ochelen, & Proost, 1996). Expected transition from oil-based to electric propulsion is likely to mitigate the environmental externalities of road traffic, but not have a major impact on traffic volume and recurring congestion.1

Road users are thus faced with a social dilemma similar to the tragedy of the commons (Hardin, 1968), where the societal consequence of individual preference (i.e., traveling by car) leads to market failures (i.e., congestion). Demand-based transportation management interventions have attempted to mitigate congestion

1 Non-recurring incidents, like accidents or bad weather, further contribute to exacerbating congestion on the roads (Schrank, Eisele, & Lomax, 2012).
by discouraging car travel (Shiftan & Golani, 2005). In particular, pricing interventions, based on congestion charges, are advocated (Rouwendal & Verhoef, 2006; Vickrey, 1969). However, the lessons from the implementation of congestion charges, in Singapore, Stockholm and London, confirm that to be effective, charging must be priced extremely high (May et al., 2010). For example, the congestion charge in London has spiked considerably from £5 to ££11.5 since its inception (BBC, 2013). In many countries, pricing policies remain controversial regarding their impact on social equity and fairness, as well as public and political acceptability problems in liberal democratic societies (Eriksson, Garvill, & Nordlund, 2006; Viegas, 2001). To circumvent the difficulties of implementing congestion charging, positive incentives and rewards to change behaviour have been attempted (Ben-Elia & Ettema, 2011; Tillema et al., 2013). However, this type of intervention motivates changes mainly in departure time around the rush hour but has less impact on mode shifts. Moreover, if intervention ceases, behaviour usually relapses back to car travel during rush hours.

With the proliferation of Information and Communication Technologies (ICT), the supply of travel information has become popular (Chorus et al., 2006; Davie, 2012). ICT applications enable a better flow of information. Also, various forms of travel information systems (ATIS), such as Variable Message Signs (Hegyi et al., 2005) and more recently, real-time navigation mobile apps such as Waze, which assist travellers to make route, mode, or destination choices (Mokhtarian & Tal, 2013). The win-win rationale for information provision seemed, until recently, self-evident — rational travellers would be able to make optimal route or mode choices, thereby improving the level of service on the entire road network and mitigating congestion in the process (Ettema & Timmermans, 2006; Levinson, 2003). However, scientific research presents a more complex picture. The cognitive and affective benefits of information in relation to contending with temporal ambiguity permit many travellers to rely on it for making their travel choices (Ben-Elia & Shiftan, 2010; Ben-Elia, Erev, & Shiftan, 2008, 2013; Kemel & Parschiv, 2013). The collective or social outcome of greater information provision to individual travellers brings road traffic to converge towards a state of User Equilibrium (UE). In traffic theory (e.g., Wardrop, 1952), UE is a state resulting from the decentralized choices of fully informed rational agents competing over the shortest paths on a given transportation infrastructure with a limited capacity (Arnott, de Palma, & Lindsey, 1993). Similar to the Nash equilibrium (Nash, 1951), this state is remarkably stable, as travellers are unlikely to change their route or mode choices, given that they are well aware (i.e., fully informed) that all other options are identical or worse. Moreover, as all drivers sharing the same routes between given origins and destinations incur more or less the same average travel costs, UE can also be regarded as an equitable (even fair) state, and this attribute allows UE to remain stable. Studies show attaining UE is positively associated with the amount of information available to travellers in the network (Lu et al., 2014; Selten et al., 2007). However, providing travellers with prevailing travel information may have negative consequences, namely the three effects raised by Ben-Akiva, De Palma, and Isam (1991) — oversaturation, overreaction and concentration. These negative effects have been confirmed in various studies. Travel information was found to create cognitive overload (Mahmassani et al., 2003), increased switching rate (Mahmassani & Liu, 1999; Srivivasan & Mahmassani, 1999) and even increase in congestion (Arnott, de Palma, & Lindsey, 1991; Jayakrishnan, Mahmassani, & Hu, 1994; Mahmassani & Jayakrishnan, 1991; Mahmassani, Hu, & Jayakrishnan, 1992). Furthermore, concrete adverse effects of information provision have also been identified under both recurring and non-recurring congestion (Emmerink et al., 1995a, 1995b; Lindsey et al., 2014; Lu et al., 2014). As the reality of urban mobility seems to be evolving towards this fully informative state, congestion management strategies built mainly on information provision seem unlikely to be making traffic flow more efficient.

Rationality and selfishness, the basic behavioural assumptions of traffic theory, have been widely criticized by behavioural economists and psychologists as not fitting the limitations of human cognition (Bolton & Ockenfels, 2000; Fehr & Schmidt, 1999; Kahneman & Tversky, 1979; Simon, 1955). Rationality has also been criticized in the transportation literature (Avineri & Ben-Elia, 2015; Ben-Elia & Avineri, 2015a, 2015b), and even social influence by others has recently been addressed (Abou-Elid & Ben-Akiva, 2011). However, selfishness has remained virtually untouched, as stated by Daniel McFadden, recognized as the “forefather” of travel behaviour modelling: “new results challenge the standard assumption of maximization of individualistic utility, indicating that social networks as information sources, reciprocity, and altruism enter human behaviour and cannot be ignored” (McFadden, 2015, p. 37). Thus travellers are not necessarily selfish “Homo Economics”, but can be understood as “Homo Socio-Logicus”, a social animal (Hirsch, Michaels, & Friedman, 1987).

Traffic theory assumes that in heterogeneous and asymmetrical networks, UE is usually suboptimal, reflecting the average travel cost, whereas marginal costs (that also internalize congestion externalities) reflect a routing allocation based on the state of system optimum (SO).² In contrast to UE, SO is an efficient traffic assignment, which minimizes the total travel costs, but this state is hard to maintain due to inherent cost inequalities drivers are expected to incur. Under SO, some travelers are obligated to take longer routes, which are less than optimal, on an individual level, from their own rational and selfish viewpoint. While SO-based traffic assignment and the travel information derived by it have been examined (e.g: Peeta & Mahmassani, 1995; Mahmassani and Peeta, 1993,1995), the specific travel behaviour emerging under an SO-based assignment has not been sufficiently examined, as the previous studies had assumed 100% compliance to the SO travel information. A more relaxed version of SO assignment, that includes a lower degree of inequality between the travelers by compromising the absolute SO state was suggested by several researchers (Angelelli et al., 2016; Jahn et al., 2005; Schulz & Stier-Moses, 2006). However, they also assume full compliance. Consequently, without some sort of centralized enforcement or coercive forms of intervention, e.g., congestion charging (Smith, Eriksson, & Lindberg, 1995; Yang & Huang, 2004; Yang, 1999) or entrance quotas (Youn, Gastner, & Jeong, 2008), SO would quickly relapse back to UE. Unsurprisingly, SO has been regarded in the literature mostly as a theoretical construct, which is not likely to be attained in real road networks. In this context, innovations in ICT open up new and uncharted possibilities to mitigate and possibly prevent the formation of congestion, and even achieve system optimal conditions, through strategies based on cooperation.

Travellers commonly make a wide range of spatiotemporal decisions such as location choice of origins (e.g., home) or destinations (e.g., work), transport mode, route, and departure time. These are ordered according to the permanency of the decision and relate to the series of models that constitute the activity-based approach (e.g., work), transport mode, route, and departure time. These are the basic behavioural assumptions of traffic theory, have been widely criticized by behavioural economists and psychologists as not fitting the limitations of human cognition (Bolton & Ockenfels, 2000; Fehr & Schmidt, 1999; Kahneman & Tversky, 1979; Simon, 1955). Rationality has also been criticized in the transportation literature (Avineri & Ben-Elia, 2015; Ben-Elia & Avineri, 2015a, 2015b), and even social influence by others has recently been addressed (Abou-Elid & Ben-Akiva, 2011). However, selfishness has remained virtually untouched, as stated by Daniel McFadden, recognized as the “forefather” of travel behaviour modelling: “new results challenge the standard assumption of maximization of individualistic utility, indicating that social networks as information sources, reciprocity, and altruism enter human behaviour and cannot be ignored” (McFadden, 2015, p. 37). Thus travellers are not necessarily selfish “Homo Economics”, but can be understood as “Homo Socio-Logicus”, a social animal (Hirsch, Michaels, & Friedman, 1987).

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² The gap between UE and SO can be referred as “the price of anarchy” (Koutsopoulos & Papadimitriou, 2009; Mak & Rapoport, 2013).
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