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Modeling lane-changing behavior in a connected environment: A game theory approach

Alireza Talebpour [a], Hani S. Mahmassani [a,*], Samer H. Hamdar [b]

[a] Transportation Center Northwestern University, 600 Foster St., Chambers Hall, Evanston, IL 60208, United States
[b] School of Engineering and Applied Science, George Washington University, 20101 Academic Way #201-I, Ashburn, VA 20147, United States

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ABSTRACT

Vehicle-to-Vehicle communications provide the opportunity to create an internet of cars through the recent advances in communication technologies, processing power, and sensing technologies. A connected vehicle receives real-time information from surrounding vehicles; such information can improve drivers' awareness about their surrounding traffic condition and lead to safer and more efficient driving maneuvers. Lane-changing behavior, as one of the most challenging driving maneuvers to understand and to predict, and a major source of congestion and collisions, can benefit from this additional information. This paper presents a lane-changing model based on a game-theoretical approach that endogenously accounts for the flow of information in a connected vehicular environment. A calibration approach based on the method of simulated moments is presented and a simplified version of the proposed framework is calibrated against NGSIM data. The prediction capability of the simplified model is validated. It is concluded the presented framework is capable of predicting lane-changing behavior with limitations that still need to be addressed. Finally, a simulation framework based on the fictitious play is proposed. The simulation results revealed that the presented lane-changing model provides a greater level of realism than a basic gap-acceptance model.

1. Introduction

Game theory has been applied in different disciplines in order to understand, analyze and model decision-making processes (Petrosjan and Mazalov, 2012). In addition to its application in the domains of economics, politics and sociology, the theory was adopted in the engineering field to explore the presence of more efficient wireless network communications (Han et al., 2012). One area of interest that bridges the gap between human decision-making and wireless communications is that of connected vehicles systems, possibly with some degree of autonomous driving. Connected vehicles systems require efficient Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication algorithms and appropriate driver responsiveness in order to avoid human errors that could lead to unsafe and congested traffic conditions. Computer scientists and engineers have focused on the security, safety and privacy of vehicular communications (Qianhong et al., 2010; Xiaodong et al., 2007) in connected environments. However, two critical questions regarding the traffic flow aspects need to be answered: (1) How to capture and specify the driving behaviors (tactical and operational) in a connected vehicle

* Corresponding author. Tel.: +1 847 491 2276; fax: +1 847 491 3090.
E-mail address: masmah@northwestern.edu (H.S. Mahmassani).

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environment, and (2) How to translate such behaviors into efficient/practical V2V and V2I communication logic in that environment.

Addressing the above questions requires proper driver behavioral modeling (for which this paper proposes using game theory), efficient algorithmic implementation and accurate trajectory data based calibration. The corresponding efforts should lead to a connected vehicle framework for reducing congestion and decreasing crash rates. Particularly, V2V communications and V2I communications provide the opportunity to create a ''network'' of vehicles through the recent advances in communication technologies, processing power, and sensing technologies. Connected Vehicles technology enhances the effectiveness and reliability of drivers' strategic, tactical, and operational decisions. Even though the impact of this technology is significant at the strategic level (for instance, accurate real-time information about roadway conditions can improve drivers' route choice decisions), drivers' operational and tactical decisions will also be influenced, and thus constitute the focus of this paper.

Acceleration and lane-changing decisions are drivers' main operational and tactical decisions. Lane changing is considered as one of the most challenging driving maneuvers to understand and to predict, and the corresponding driving decisions are often seen as a major source of congestion and collisions. While acceleration behavior (especially car-following behavior) has been studied extensively since the 1950s and many different models with different assumptions have been proposed to capture drivers' car-following and free-flow behaviors, only few lane-changing models have been presented in the literature. Moreover, most existing lane-changing models are rule-based models (Gipps, 1986; Hidas, 2002; Kesting et al., 2007) that do not take into consideration stochasticity and uncertainty. While some models adopt more realistic utility-based approaches to capture drivers' decision-making processes (Ahmed, 1999), they do not explicitly consider the dynamic interactions among drivers and cognitive decision features. Moreover, most of these models are not formulated to consider the flow of information in a connected environment. To address such shortcomings, the main objective of this paper is to develop a lane-changing model that endogenously accounts for the flow of information in a connected vehicular environment. Towards realizing this objective, a game-theoretical approach inspired by early works of Kita and his colleagues (Kita, 1999; Kita et al., 2002) is adopted. Game theory provides the foundation to capture the dynamic interactions between drivers in a lane-changing maneuver. This approach suggests two game types:

- **Game 1: two-person non-zero-sum non-cooperative game under complete information:** this type of game represents lane-changing decisions in a connected environment. Through V2V communication, we assume that drivers are certain about other drivers' decisions. In addition to the information about other drivers' decisions, V2V communication may reduce the uncertainty related to the game payoffs. Payoffs reflect the drivers' utility gain from choosing different strategies and depend on the drivers' preferences and characteristics.
- **Game 2: two-person non-zero-sum non-cooperative game under incomplete information:** This type of game represents lane-changing decisions that are made when drivers are uncertain about other drivers' decisions. Such uncertainty may lead to mandatory or discretionary lane-changes (Ahmed, 1999) depending on the drivers' willingness to take risks.

Moreover, a calibration approach based on the method of simulated moments (MSM) is presented and the modeling framework is calibrated against Next-Generation Simulation (NGSIM) data (Federal Highway Administration, 2007). MSM possesses good small sample properties and thus provides an unbiased and consistent estimator for a fixed number of simulations. Validation of the proposed approach is also presented. An efficient simulation approach based on fictitious play and learning in games is presented. The approach assumes that drivers play a repeated game until a Nash equilibrium is reached (Nash, 1951).

The remainder of the paper is organized as follows: Section 2 presents a brief review of major game-theory applications in transportation engineering along with a review of some essential lane-changing models. The modeling framework is presented in Section 3 and the logic behind formulating the two games mentioned earlier is discussed. A MSM based calibration approach is offered in Section 4. The corresponding section is followed by a discussion on the model validation in Section 5. Finally, Section 6 illustrates the fictitious play based simulation approach before concluding with some summary remarks and future research needs in Section 7.

2. Background

In addition to the game theory applications in different science and engineering fields mentioned in Section 1, game theory has been adopted multiple times in transportation analysis (He et al., 2010). The main game theory models used are: (1) ordinary non-cooperative game, (2) generalized Nash equilibrium game, (3) Cournot game, (4) Stackelberg game, (5) bounded rationality game and (6) repeated games. The corresponding transportation analysis types may be mainly classified as: (a) macro-policy analysis (including i. games between travelers and authorities, ii. games between authorities, and iii. games between travelers) and (b) micro-behavior simulation (including i. games between travelers and authorities and ii. games between travelers). These studies focused mainly on vehicular traffic and on the strategic decision making level (i.e. route choice, departure time choice, destination choice and mode choice) (Bell, 2000; Fisk, 1984; Hollander and Prashker, 2006; Tosin, 2008; Wang et al., 2013). As for the shorter tactical and operational decision making time frame,