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A two-dimensional simulation model for modelling turning vehicles at mixed-flow intersections

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ABSTRACT

The turning behavior is one of the most challenging driving maneuvers under non-protected phase at mixed-flow intersections. Currently, one-dimensional simulation models focus on car-following and gap-acceptance behaviors in pre-defined lanes with few lane-changing behaviors, and they cannot model the lateral and longitudinal behaviors simultaneously, which has limitation in representing the realistic turning behavior. This paper proposes a three-layered "plan-decision-action" (PDA) framework to obtain acceleration and angular velocity in the turning process. The plan layer firstly calculates the two-dimensional optimal path and dynamically adjusts the trajectories according to interacting objects. The decision layer then uses the decision tree method to select a suitable behavior in three alternatives: car-following, turning and yielding. Finally, in the action layer, a set of corresponding operational models specify the decided behavior into control parameters. The proposed model is tested by reproducing 210 trajectories of left-turn vehicles at a two-phase mixed-flow intersection in Shanghai. As a result, the simulation reproduces the variation of trajectories, while the coverage rate of the trajectories is 88.8%. Meanwhile, both the travel time and post-encroachment time of simulation and empirical turning vehicles are similar and do not show statistically significant difference.

1. Introduction

Intersections are the main bottlenecks of road network and the hot spots of traffic safety. At mixed-flow intersections, turning vehicles interact with both the motorized and non-motorized straight-going traffic under non-protected phase. Besides, there is no obvious lane discipline within intersections. These factors lead the turning behavior to the most challenging driving maneuver. In previous studies, some significant characteristics of turning vehicles have been discovered. Firstly, the trajectories of turning vehicles change dynamically under the impact of intersection geometry, traffic conflicts and priority rules (Alhajyaseen et al., 2013). What's more, decision behavior of turning vehicles is influenced by dynamic factors (Kaysi and Abbany, 2007) such as gaps (Pollatschek et al., 2002), speed (Alexander et al., 2002) in the opposing traffic stream, relative speed of conflicting vehicles (Liu et al., 2014) and waiting time of the turning vehicles (Mahmassani and Sheffi, 1981). Moreover, traffic participants do not always act according to traffic regulations (Björklund and Åberg, 2005; Bai

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et al., 2013): the priority of the straight-going drivers may be limited by gap forcing behavior of the drivers of turning vehicles or cooperative priority sharing behavior of themselves, namely limited priority phenomenon (Troutbeck and Kako, 1999; Kaysi and Alam, 2000; Brilon and Wu, 2002; Bunker and Troutbeck, 2003). Besides, different types of traffic participants may have their respective understanding of priority order and compete the right of way, namely non-strict priority phenomenon (Räsänen et al., 1999; Liao et al., 2015). Last but not the least, turning behavior requires multi-tasking ability of drivers including perceiving traffic environment, processing information, acting correctly and probably cooperating with others (Sun, 2005). Since complex turning behavior is vital for traffic control and safety evaluation of an intersection, a well-performed simulation model is required to reproduce the complexity and variation of turning vehicles with high resolution.

In the past decades, the most popular models to simulate turning behavior are one-dimensional models. They can be defined as a set of lane-based models in which longitudinal movement is captured by a car-following model and lateral movement is separately modeled by a lane-changing model. The advantages are their simplicity and applicability for combining with decision-making process. However, the variation of turning trajectories cannot be reproduced (Huang et al., 2012). Compared with the one-dimensional models, the two-dimensional model breaks the lane-based assumption. It can simulate longitudinal and lateral behaviors simultaneously and better reflect the characteristics of the turning behavior.

However, the concept of the two-dimensional simulation will bring more challenges to simulation process. Present models based on the gap-acceptance theory can predict the future traffic condition easily (e.g. PTV, 2010). In the two-dimensional simulation, it is hard to predict gap value and make a crossing decision. The potential conflicting points and the time taken to reach the points are time-varying. In addition, in the mixed flow, different decision rules may be applied in interacting with the motorized and non-motorized flow. Furthermore, without the lane discipline, the control of steering wheels is difficult to be obtained. The angular velocity of vehicular movement is not only related with the geometry of intersection, but also with the vehicle interaction. For example, the angular velocity is different when drivers prepare to cross different gaps. Moreover, the phenomena of the limited and non-strict priority are more complex to simulate in the two-dimensional simulation. Aggressive turning drivers may not only adjust their speed when competing the right of way (Liao et al., 2015) but also adjust their steering behavior to occupy a favorable position.

To deal with these challenges, a novel two-dimensional simulation model has been designed. It contains a human-like driving process and calculates the acceleration and angular velocity of turning vehicles simultaneously. The focus of the model is adjusted from the behavior in lanes to the behavior in space. The main contributions of this study are as follows. Firstly, the proposed model is formulated as a three-layer "plan-decision-action" (PDA) framework which is able to simulate the complete dynamic driving process of turning vehicles. Secondly, a multi-stage trajectory plan model is proposed to handle the interaction with other objects as well as constraints of vehicle dynamics. Thirdly, three rule-based decision criteria are used to separate different traffic patterns. Among them, the turning criterion is established with the decision tree method, which allows for the limited priority and non-strictly priority in mixed-flow intersections. The model is tested by using field data, with satisfactory performances obtained.

The rest of this paper is organized as follows. Section 2 presents the literature review about the present turning behavior models. Section 3 introduces the "plan-decision-action" framework of the two-dimensional simulation model and each component in detail. The results of the case study that implements the proposed model are analyzed in Section 4. Finally, Section 5 presents the conclusion and the direction of the future research.

2. Literature review

In previous studies, classical models (i.e. car-following, lane-changing and gap-acceptance models) and Cellular Automata (CA) are of the most popularity to simulate the motion process of turning vehicles. Besides, social force model is recently used to model vehicles and pedestrians in shared space including intersections. Because of distinct modelling ideas, each approach is reviewed individually, by which the strengths and weaknesses of these three approaches are compared.

The classical models are widely adopted by commercial simulation software. Car-following, lane-changing and gap-acceptance models are fundamental components. Within intersections, car-following model explains the longitudinal movements of vehicles on a single path, while lane-changing behavior is seldom specified. Gap-acceptance model is the key component and it explains the binary choice of crossing or merging behavior. More specifically, drivers compare the available gap with the critical gap. If the former is smaller, drivers reject the gap. If not, drivers accept it. The critical gap is considered as a random variable obeying a certain distribution, e.g. exponential distribution, gamma distribution, lognormal distribution and normal distribution. To analyze the binary choice, several studies used logit (Cassidy et al., 1995; Devarasetty et al., 2012) and probit model (Mahmassani and Sheffi, 1981; Kaysi and Abbany, 2007) which assumes the average critical gap as a function of explanatory variables and allows for the difference among drivers. The classical models explicitly handle the vehicular interaction by deciding whether to accept gaps. However, these models also have some drawbacks. In the perspective of vehicular motion, as mentioned above, only one-dimensional movement is modeled, which is not capable to represent the realistic turning behavior. Regarding the decision making process, the information for estimating the critical gap is extracted from drivers who accept a gap after queueing (Brilon et al., 1999). Thus the results may not be suitable for the dynamic decision of the approaching vehicles in simulation. Meanwhile, the underlying assumption of the model is the deterministic priority order, which does not represent the phenomena of limited priority or non-strict priority (Brilon and