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Characteristics of traffic flow at a non-signalized intersection in the framework of game theory

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HIGHLIGHTS

- We model the traffic flow at the non-signalized intersection.
- The model introduces the game theory into simulating the traffic flow of non-signalized intersection.
- We use the Weibull distribution to describe driver's behavior.
- We found one transition regime in the phase diagram.
- The existence of defectors is benefit for the capacity of intersection, but also reduces the safety of intersection.

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ABSTRACT

At a non-signalized intersection, some vehicles violate the traffic rules to pass the intersection as soon as possible. These behaviors may cause many traffic conflicts even traffic accidents. In this paper, a simulation model is proposed to research the effects of these behaviors at a non-signalized intersection. Vehicle's movement is simulated by the cellular automaton (CA) model. The game theory is introduced for simulating the intersection dynamics. Two types of driver participate the game process: cooperator (C) and defector (D). The cooperator obey the traffic rules, but the defector does not. A transition process may occur when the cooperator is waiting before the intersection. The critical value of waiting time follows the Weibull distribution. One transition regime is found in the phase diagram. The simulation results illustrate the applicability of the proposed model and reveal a number of interesting insights into the intersection management, including that the existence of defectors is benefit for the capacity of intersection, but also reduce the safety of intersection.

1. Introduction

The urban traffic system includes many different facilities such as various level roads and structure intersections. That means vehicles moving in urban traffic must face complex environment, and drivers have to make decisions from time to time to move safely as well as quickly. The unreasonable or wrong decision will make the traffic conditions worsen. The terrible traffic causes many environmental issues such as smog and noise pollution, and huge economic losses. In order to

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improve the traffic condition, it is very important to understand the form mechanism of traffic congestion in a certain traffic environment, and then identify optimal control strategies to help alleviate the traffic congestion.

The study of traffic flow theory and modeling started in 1930s, pioneered by Bruce D. Greenshields [1]. He first used photographic measurement methods to measure traffic flow, density and velocity. A model of uninterrupted traffic flow was developed to predict and explain the trends which are observed in real traffic. However, since the 1990s, the field has gained considerable attraction due to the increase of traffic demand and the advance of computing power. In order to investigate the dynamical behavior of traffic flow, many traffic models such as hydrodynamics models [2–4], gas-kinetic-based models [5,6], car-following models [7–9] and cellular automaton models [10–12] have been proposed by physicists. Among these models, cellular automaton (CA) models have been extensively applied and investigated, because they can reproduce many realistic phenomena and are easy to simulate the traffic system fast. The Nagel–Schreckenberg (NaSch) model is a basic CA model describing one-road traffic system [10]. Based on the NaSch model, many CA models have been extended to investigate the properties of the system with realistic traffic factors.

The intersection is very important facility in the urban traffic system. The capacity of intersection restricts the efficiency of the urban traffic network. In order to research the characteristics of traffic flow at the intersection, many simulation models [13–21] are proposed. These models generally include two parts: vehicles movement on the road and the dynamical behaviors at the intersection. These models deal with the conflicts at the intersection by some rules such as first come first pass, assigning the right-of-way according to the given hierarchy. In real traffic, drivers have different drive behaviors. Various vehicles at the intersection may adopt different strategies to resolve the obvious traffic conflicts. This process is very similar to the game theory including players, strategies, and payoff. The game theory [22–25] is introduced to deal with the problems that how to assign the right-of-way between the vehicles. These methods can reflect the vehicle behaviors in a more flexible and realistic way in the traffic system.

Non-signalized intersection is a very common facility in urban traffic. When the different direction vehicles meet at the non-signalized intersection, they should obey the basic traffic rule. Namely, the right-of-way can be only given one vehicle and the vehicle on the main road has the priority to get it. But if the waiting time for the right-of-way exceeds drivers' endurance limit, they will change their behaviors and disobey this rule. All the drivers can be classified into two types: cooperator (C) and defector (D). These two types of drivers adopt different behaviors when they face different situations. For example, the defector on the side road will obtain the right-of-way of intersection forcibly or conflict with the other defector at the non-signalized intersection. The effect of this behavior is not very clear at the intersection. In order to study the effect, a simulation model is established, including two parts: vehicle movement and intersection dynamics. The vehicle movement is simulated by a cellular automaton model. The Weibull distribution is used to describe the behavior change probability. The intersection dynamics is described in the framework of game theory. The remainder of the paper is organized as follows. In Section 2, the details of the simulation model are illustrated. In Section 3, the numerical simulation is carried out and the simulation results are analyzed. The concluding remarks are made and future research directions are briefly discussed in the Section 4.

2. Model formulation

In this section, a simulation model is proposed to depict a non-signalized intersection system. Fig. 1 is the sketch of the analyzed non-signalized intersection system. This traffic system includes two crossed roads. Each road is the unidirectional road and has a single lane. Road 1 is the main road and permits vehicles to move from west to east. Road 2 is the side road and permits vehicles to move from south to north. The cross point X of two roads is located at the middle of the road. For simplicity, there are no turning vehicles in this traffic system.

2.1. The vehicle movement model

Cellular automata models are wildly used in traffic simulation. According to the difference of research problems, it is necessary to establish an appropriate cellular automaton model. The NaSch model [10] is the first and simplest cellular automaton model which is actually used for traffic flow simulations. Although its rules are very simple, it can reproduce many basic phenomena in realistic traffic, such as the start–stop waves. In this paper, our research focus is the behavior of vehicles at the intersection not the movement of vehicles on the road. So the NaSch model is suitable for simulating the vehicle movement on the road. In the NaSch model, space is divided into cells and time is divided into time steps. In this intersection system, the length of each road is divided into L cells. The cross point X of two roads is the $L/2$th cell. Each cell has two conditions, occupied or empty. All cells can be occupied by only one vehicle except the $L/2$th cell. The $L/2$th cell can be occupied by two different direction vehicles in some special situations. Each vehicle has a time-dependent speed $v_i(t)$ that takes discrete values $0, 1, 2, \ldots, v_{\max}$; here $v_{\max}$ is the maximum speed. The update rules of the NaSch model in each iteration step are as follows, which are performed in parallel for all vehicles:

- Step1: deterministic acceleration:

$$v_i(t+1) = \min(v_i(t) + 1, v_{\max}, \mathrm{gap}_i). \tag{1}$$