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Optimization strategy for and structural properties of traffic efficiency under bounded information accessibility

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HIGHLIGHTS

- We introduce a new model which is more sensitive to the reality than previous models.
- We propose two main factors for traffic efficiency, section area and symmetricity.
- We find the optimal point for traffic efficiency, which causes the phase transition.
- We find the optimal structure for traffic under bounded information accessibility.
- We carry out investigation into empirical study for credibility of our numerical simulation.

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ABSTRACT

A vital challenge for many socioeconomic systems is determining the optimum use of limited information. Traffic systems, wherein the range of resources is limited, are a particularly good example of this challenge. Based on bounded information accessibility in terms of, for example, high costs or technical limitations, we develop a new optimization strategy to improve the efficiency of a traffic system with signals and intersections. Numerous studies, including the study by Chowdery and Schadschneider (whose method we denote by ChSch), have attempted to achieve the maximum vehicle speed or the minimum wait time for a given traffic condition. In this paper, we introduce a modified version of ChSch with an independently functioning, decentralized control system. With the new model, we determine the optimization strategy under bounded information accessibility, which proves the existence of an optimal point for phase transitions in the system. The paper also provides insight that can be applied by traffic engineers to create more efficient traffic systems by analyzing the area and symmetry of local sites. We support our results with a statistical analysis using empirical traffic data from Seoul, Korea.

1. Introduction

Traffic flows represent various and intriguing complex phenomena. Numerous studies of traffic system problems have motivated research by physicists due to their statistical and dynamical features [1–11]. Due to the inherent properties of a traffic system, an agent-based model (ABM) has been employed to study traffic dynamics. We can classify a traffic system with an ABM into two categories for study: pedestrian dynamics and vehicle dynamics. Pedestrian problems have been investigated with microscopic models, including the cellular automata (CA) model [10–16], the social force model [5,17,18],

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the magnetic force model [19] and the centrifugal force model [6]. In contrast to pedestrian problems, vehicle problems focus not only on individual behavior but also on the structural effect of important variables. The traffic signal is one of the most important variables for describing a phase transition, such as the transition from the jam phase to the free-flow phase [7,20,21]. Although numerous studies about traffic jams, chaotic traffic flows, pedestrian flows, and the sequence of traffic signals have been performed [22–27], few studies have addressed system efficiency. System efficiency is defined as the ratio of the increase in traffic flow to the cost of using traffic signals to create more efficient traffic conditions in an urban traffic system. The control of efficient traffic signals is important for improving mobility and reducing the wait time of vehicles on the road because intersections are the most common reason for speed reductions in a large city [28]. The jam state of a traffic system increases the wait time or reduces vehicle speeds. To mitigate the jam state, various studies have been intensively performed in many disciplines, and brilliant mathematical and numerical models have been introduced.

We discuss the ChSch model because it is the simplest toy model available for developing the decentralized control concept with as few variables as possible. Previous studies have examined decentralized and self-organized traffic signal control [7,29]. However, we focus on an independently functioning decentralized control system to determine the association between the real world and the numerical model using a simplified toy model. Although most parameters vary, we select identical values for all vehicles to minimize the number of parameters, facilitate calibration, achieve robustness and exclude irregular results due to parameter variations. We ensure that this approach simplifies the model for use in various studies.

The ChSch model simulates urban traffic with intersections [30,31]. The model combines two previously suggested models the Biham–Middleton–Levin (BML) model [24,32] and the Nagel–Schreckenberg (NaSch) model [33,34]; two-dimensional space is extracted from the BML model, and traffic signals are extracted from the NaSch model. This combination produces a realistic traffic model with two major factors concerning traffic jams: the movements of vehicles and the control of traffic signals. Brockfeld and Barlovic [1] investigated the nature of the modified ChSch model using several global traffic strategies and concluded that a rule named the Green Wave Strategy (GWS) outperforms other strategies for both low and high vehicle densities. The GWS has an offset parameter, with which the switching time of adjacent traffic signals is delayed. The majority of these studies have attempted to improve traffic conditions in regard to the mean flow, which is the average distance for the movement of all vehicles. All variables, such as traffic signals, movement of vehicles and density of vehicles, control the traffic phase from the jam phase to the free-flow phase or vice versa. The strategy can enhance traffic conditions via other approaches [35,36]. The GWS is the best strategy, because it incorporates all information on a simulation map, which results in high costs and inefficient in use.

In this paper, we focus on the bounded range of information to control a traffic signal system by considering the related high costs and technical limitations. This method exhibits more affinity with real traffic conditions because districts independently manage pedestrians and vehicles in actual urban traffic situations [37–39]. If information is limited in a traffic system, namely by the restriction of the interlocking range of traffic signals, the efficiency of a traffic system will vary based on the information range. Considering limitations on actual information about an urban traffic system caused by technical issues, we analyze the effect of limited information to obtain a meaningful solution. The limited information causes the entire map to be partitioned into various independent divisions. Each division is physically connected; however, independent players are functionally considered. In addition, the area and symmetry when the system is divided into small lots is considered. Thus, we investigate not only the amount of information compared to the size of each section area but also the effect of the rectangular symmetry of the local site. We determine if two parameters can fulfill their roles as valuable components that are properly based on the empirical data of Seoul, which is also known as the capital city of South Korea.

This paper is organized as follows: In the following section, the definition, characteristics and regulation of the model used in the simulation are presented. We attempt to modify the ChSch model to prevent gridlock of vehicles as presented by Ref. [30] and introduce several parameters to assess the nature of our model. In Section 3, the mean flow (equivalent to the concept of velocity flow), which is introduced under various limited information circumstances, is tested via numerical simulation. The results with the alteration of several parameters and the interpretation of the simulations are presented. A newly defined symmetricity is proposed to test the role of symmetry in traffic efficiency. We provide a comparison between the numerical simulation data and the empirical data. Section 4 presents a discussion of the obtained results and of the highlights of the study.

2. Models and strategies

2.1. Model settlement

The ChSch model reflects two critical features of actual urban traffic: numerous vehicles and traffic signals [30]. The entire map is composed of $N \times N$ intersections connected by streets with a length L, including traffic signals; thus, $L - 1$ cells represent single streets. Fig. 1 shows a snapshot of our simulation model. Every street consists of a set of cells that forms a square lattice. The total number of cells for each successive street is $L_T = NL$. After establishing the map with intersections and traffic signals, vehicles are randomly scattered with a given density ρ. The ChSch model contains only two direction-bound vehicles; the number of eastbound vehicles and northbound vehicles are identical. A periodic boundary condition is applied to conserve the number and directions of the vehicles. The total number of vehicles in the entire map