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A unified follow-the-leader model for vehicle, bicycle and pedestrian traffic

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ABSTRACT

In this research we performed new bicycle and pedestrian experiments to supplement data extracted from existing follow-the-leader experiments in vehicles, bicycles and pedestrians, and studied their spacetime trajectories and flow-density (or spacing-velocity) phase diagrams. The strong similarities in the spacetime trajectories and the bi-variate phase plots as well as the relative consistence of the estimated proportionality parameter across all three types of traffic, suggest that a unified behavioral mechanism is at play in human-driven traffic. It is suggested that this mechanism is essentially a safety-driven behavior that vehicles, bicycles or pedestrians adopt a safe speed for a given spacing between them. This behavior is well described by a well-known model in vehicular traffic and it is shown in this paper that a scaled version of this model applies to all three types of traffic. A unified relaxation-driven social force traffic model is then proposed to incorporate this behavior mechanism. Simulations with the same setup as the real-life experiments were carried out for vehicle, bicycle, and pedestrian traffic using the unified traffic model and the simulated spacetime trajectories and fundamental diagrams show remarkable consistence with the experimental results.

1. Introduction

Biking and walking, often known as low-carbon or green transportation, have been actively promoted for decades. As the concern for climate change intensifies, more investment in the green transportation infrastructure is anticipated, and as a result, cities residents will see and experience more frequently the traffic of vehicles, bicycles and pedestrians either in dedicated or shared facilities. In order to plan and operate such facilities more effectively and promote green transportation, it is vital to understand the characteristics and behaviors of these three different kinds of traffic systems as well as the relationships among them.

In the past these different types of traffic systems have usually been studied separately. For instance, pedestrian traffic dynamics has been studied using statistical physics models including the social force model proposed by Helbing (Helbing and Molnar, 1995; Helbing et al., 2000a,b), cellular automation models (Burstedde et al., 2001; Kirchner and Schadschneider, 2002; Kirchner et al., 2003), lattice gas models (Muramatsu and Nagatani, 2000; Tajima and Nagatani, 2002; Maniccam, 2003; Helbing et al., 2003), and so on. These theoretical models provide significant insights into pedestrian traffic dynamics

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and help the preparation of design guidelines for transportation and the building environment (Pelechano and Malkawi, 2008; Zhao et al., 2008; Chow and Ng, 2008; Seyfried et al., 2009; Xu and Song, 2009), as well as devising strategies for evacuations in disasters such as fires, tsunamis, and earthquakes (Weckman et al., 1999; Rassia and Siettos, 2010; Lämmel et al., 2010). As for the study of bicycle traffic dynamics, the majority of the work concentrated on bike traffic operating characteristics, bike speed distributions, and bike lane capacities (Taylor and Davis, 1999). Only a few studies focused on cycling behavior and flow properties of bicycle traffic (Andresen et al., 2014). Automobile traffic flow dynamics has been researched extensively and the literature is too vast to list here. We want to point out one relevant aspect of vehicular traffic here, it is the emergence of a traffic jam as a dynamical phase transition from stable to unstable traffic flow when the vehicular density exceeds a critical value (Sugiyama et al., 2008; Tadaki et al., 2013; Tadaki et al., 2015).

Given the fact that all three traffic systems are driven by human beings in well delineated environments with similar rules and goals, one would expect that they may share some fundamental features that are intricately linked to human behavior and capabilities. Recently, single-file bicycle experiments in circuits have been performed and compared with previous studies for pedestrian and car motion in similar setups (Zhang et al., 2013; Zhang et al., 2014). Three different motion states of free flow, jammed flow and stop-and-go waves are all observed in all these systems. It was found that a unified flow-density relation exists for bike and car traffic after proper rescaling of space and time which takes into account the maximum velocity and the size of the moving objects.

However, in the car experiment in Japan, only a total of two runs are carried out with the number of cars $N=22$ and 23 inside the circuit in these studies, thus further car empirical data are still needed especially in the higher density range for car traffic. Similarly, bicycle traffic data in the high density range are also quite scarce in the bicycle experiment performed in Germany because traffic congestion and stop-and-go waves are not apparent with the number of bicycles $N=33$. Finally, the pedestrian experiment in Germany was performed by soldiers which, particularly regarding walking, do not constitute a representative group of the general population. Therefore, further experiments should be performed by normal pedestrians with a natural heterogeneity.

Moreover, although the flow-density relations of single-file car, bicycle and pedestrian motion can be unified in a certain range by a simple scaling of velocity and size, the essential physical mechanisms which lead to the similarities among the fundamental diagrams of these three traffic systems are still unclear. Especially, it is also unknown whether the characteristics and behaviors of pedestrian, bicycle and car traffic systems can be described by a unified traffic model.

In this paper, we will firstly carry out new bicycle and pedestrian experiments in China with high precise trajectories covering the whole spectrum of traffic conditions on circular tracks. Then we will present the experimental evidence that the similarities among the spacetime trajectories and fundamental diagrams of these three traffic systems are actually the result of a unified psychology-driven behavior of the pedestrians, cyclists and car drivers to balance the desire for speed and safety: a person has to stop to avoid a collision if his headway is below a critical value, and he is eager to reach the maximum desired velocity if the headway is large enough. When their motions are constrained by surrounding objects (pedestrians, bicycles or cars), the desired velocities of the travelers are studied and found to have a linear relationship with their headways. A unified dynamic traffic model that incorporates this behavioral mechanism is also proposed and simulations are carried out to compare the spacetime trajectories and fundamental diagrams of car, bicycle and pedestrian traffic obtained from the simulations with those from the experiments.

The rest of the paper is organized as follows. In Section 2, we describe the details of new bicycle and pedestrian experiments in China from which we obtained our data and present the spacetime trajectories and fundamental diagrams of car, bicycle and pedestrian traffic revealed from the data. In Section 3 we propose a behavioral mechanism to explain similarities in the observed spacetime trajectories and fundamental diagrams. In Section 4 we go one step further and propose a unified traffic model to reproduce the spacetime trajectories and fundamental diagrams observed in the car, bicycle and pedestrian experiments. Finally, we conclude the paper in Section 5 by providing a summary and discussion.

2. The car, bicycle and pedestrian experiments and their spacetime trajectories as well as fundamental diagrams

The car, bicycle and pedestrian experiments were all carried out on planar circuits where only single-file movement was possible. Series of experiments were performed by changing the number of participants who were asked to move normally without overtaking. Fig. 1 shows snapshots of the car experiment in Japan (Tadaki et al., 2013), the new bicycle experiment in China and the new pedestrian experiment in China respectively.

The car experiment was performed in a large indoor circuit in the Nagoya Dome, an indoor Japanese Professional League baseball field (Tadaki et al., 2013). The circuit was larger (314 m in circumference) than that used in the previous experiment (Sugiyama et al., 2008), and the trajectories of cars were observed using a high-resolution laser scanner. Different sessions were carried out with varied numbers of cars from $N=10$ to $N=40$. All of the cars were of the same model and specifications (Toyota Vitz: 1.3 L, 3.89 m long, automatic transmission), and were drove by fifty-two college students alternately. In each session of car experiment, the driver of the first car were requested to drive slowly until all the cars had entered, at which point all of the participants were instructed to drive safely in their own manner at a target velocity of 30 km/h.

A new bicycle experiment with a similar setup was carried out in China. On a circuit road with a circumference of 52 m, a series of runs were performed with different numbers of bicycles from $N=5$ to $N=23$. The participants in the bicycle experiment consisted of college students. The mean length of the bicycles was 1.57 m, and the mean weight of each participant plus his/her bicycle was 90 kg. All the cyclists were asked to ride their bicycles in anticlockwise direction. Finally,