Physics Letters A 378 (2014) 3274–3277

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Universal flow-density relation of single-file bicycle, pedestrian and car motion

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ARTICLE INFO

Article history:
Received 11 July 2014
Accepted 22 September 2014
Available online 28 September 2014
Communicated by F. Porcelli

Keywords:
Traffic flow
Self-driven systems

ABSTRACT

The relation between flow and density is an essential quantitative characteristic to describe the efficiency of traffic systems. We have performed experiments with single-file motion of bicycles and compared the results with previous studies for car and pedestrian motion in similar setups. In the space–time diagrams we observe three different states of motion (free flow state, jammed state and stop-and-go waves) in all these systems. Despite their obvious differences they are described by a universal fundamental diagram after proper rescaling of space and time which takes into account the size and free velocity of the three kinds of agents. This indicates that the similarities between the systems go deeper than expected.

1. Introduction

In the past, various studies have been performed on pedestrian [1], bicycle [2] and vehicular traffic [3–6]. Besides the obvious practical relevance, from a physics point-of-view, these traffic systems are interesting for the observed collective and self-organization phenomena, phase transitions, etc. Most of the methods and theories in pedestrian dynamics are borrowed from vehicular traffic. As for the study of bicycle traffic, most research focuses on operating characteristics, travel speed distributions as well as bicycle characteristics. Only a small number of studies focused on the flow properties of bicycle traffic [7–10]. Here we want to find out how strongly the flow-density relation depends on the properties of the agents.

Usually these different types of traffic flows are investigated separately. So far a systematic comparison has not been attempted but qualitative similarities are obvious. Nearly all studies on pedestrians and vehicles show that the speed decreases with the density. At a certain critical value of the density the flow is unstable and transits from free flow to jammed flow. This transition was also found for bicycle flows [10]. In this work single-file pedestrian, car and bicycle movement on a planar circuit will be studied under laboratory conditions. We analyze, on a quantitative level, similarities and differences between the flow-density relation of these three traffic modes. We want to study whether they can be derived from a universal flow-density relation.

2. Experimental setup

The experiments for all three types of traffic were performed with similar setups, namely on planar circuits where only single-file motion was possible. Series of experiments were carried out with a maximal number of participants $N = 70, 23$ and 33 for the pedestrian, car and bicycle experiment, respectively. In general, participants were asked to move normally without overtaking. The global density was varied by repeating the experiment with different numbers of participants.

The pedestrian experiment [11] was performed with soldiers moving in a circular corridor of the circumference $C_p = 26$ m. During the experiment the soldiers were asked to walk in a normal fashion but not in lockstep (see the video from [12]). The one dimensional global density $\rho_g = N/C$ ranges from 0.54 m^{-1} to 2.69 m^{-1} in this experiment.

A similar experiment with cars was performed by Sugiyama et al. [13,14] on a circular road with the circumference $C_c = 230$ m and $N = 22$ and 23, corresponding to global densities $\rho_g = 0.096$ m^{-1} and 0.1 m^{-1}, respectively. Recently the same group improved these experiments [15]. They carried out 19 experimental runs with $C_c = 312$ m and different numbers of cars (N was

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http://dx.doi.org/10.1016/j.physleta.2014.09.039
0375-9601/

Fig. 1. Snapshots of the bicycle experiment on a circuit road.

changed from 10 to 40). The global density ρ_g in this experiment ranges from 0.03 m^{-1} to 0.13 m^{-1}.

The bicycle experiment was carried out in Germany in 2012 with participants of all ages [16]. On a circuit road with the circumference $C_b = 86$ m several runs with different numbers of bicycles (from $N = 5$ to $N = 33$) were performed (Fig. 1). Based on video recordings [17] the trajectories were extracted automatically, similarly to the method used in the pedestrian experiments [18]. Details will be given elsewhere [16].

3. Trajectories

From the high precision trajectories, traffic flow characteristics including flow, density and velocity can be determined. Fig. 2 shows a time–space diagram in the measurement area, which has a length of 27 m, from one run of the bicycle experiment. Similar trajectory plots for car and pedestrian motion can be found in [11,13].

In all three cases a transition from free flow to jammed flow can be observed with the increasing of the global density. In the free flow regime all agents can move at their desired speed, whereas in the jammed regime typically stop-and-go waves are observed.

4. Methods of data analysis

The comparison of time–space diagrams already indicates a qualitative similarity between the three traffic systems. A deeper understanding requires quantitative analysis which allows to uncover the underlying dynamics that is not apparent in the more qualitative observations of the trajectories. We use both macroscopic and microscopic analysis to obtain more detailed information on the specific flow-density relation or equivalently the velocity-density relation. In this study the specific flow J_s is calculated by $J_s = \rho \cdot v$.

Microscopically, an individual density can either be defined based on a Voronoi tessellation [19] or the headway. The headway $d_H(i)$ is defined as the distance between the centers of mass of an agent i and its predecessor, whereas the Voronoi space $d_V(i)$, for one-dimensional motion, is the distance between the midpoints of the headway and the headway of its follower $i-1$. The corresponding individual densities are then $\rho_H(i) = 1/d_H(i)$ and $\rho_V(i) = 1/d_V(i)$, respectively. As for the individual velocity, the instantaneous velocity $v_i(t)$ is defined as

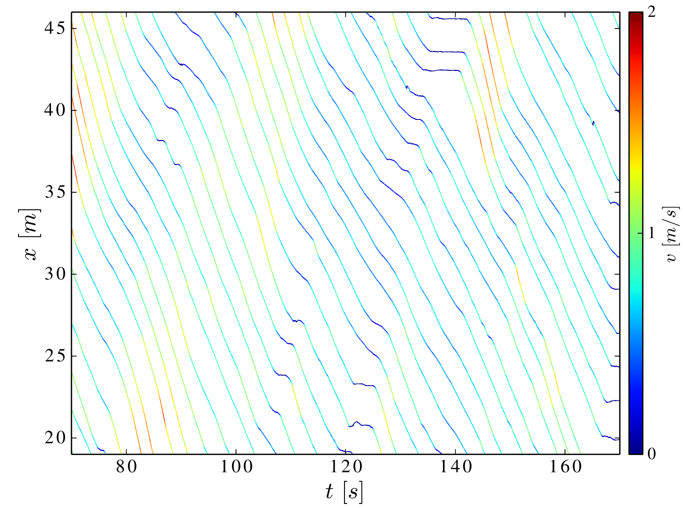

Fig. 2. Trajectories in the measurement area (of length 27 m) for the bicycle experiment with $N = 33$. The same structures can be found in trajectories of pedestrian and vehicle systems [11,13].

$$v_i(t) = \frac{x_i(t + \Delta t'/2) - x_i(t - \Delta t'/2)}{\Delta t'}, \tag{1}$$

where $x_i(t)$ is the x coordinate of pedestrian i at time t and $\Delta t' = 2$ s is used in this study.

The individual flow-density relation of bicycle traffic obtained from the Voronoi-based and headway-based methods do not show large discrepancies but the results of the headway-based method are more scattered. This has previously been observed for pedestrian dynamics [19,20].

Macroscopically, the similarities between the three systems are more apparent. On the macroscopic level the mean densities $\rho(t)$ and velocities $v(t)$ in a measurement area at time t are calculated based on Voronoi method:

$$\rho(t) = \frac{\sum_{i=1}^{n} \Theta_i(t)}{l_m}, \tag{2}$$

$$v(t) = \frac{\sum_{i=1}^{n} \Theta_i(t) \cdot v_i(t)}{l_m}, \tag{3}$$

where n is the number of agents whose Voronoi space includes the measurement area (assuming that the overlapping length between the space and the measurement area is $d_o(i)$ for agent i). $\Theta_i(t) = d_o(i)/d_V(i)$ represents the contribution of agent i to the density of the measurement area. $v_i(t)$ is the instantaneous velocity (see Eq. (1)) and l_m is the length of the measurement area.

In this study, the lengths of the measurement areas l_m were 3 m, 35 m and 13 m in the pedestrian, car and bicycle experiments, respectively. Since the (average) length of agents is 0.4 m, 3.9 m and 1.73 m, at most 7 agents can occupy the measurement area at the same time. It should be noted that in all experiments the ratio of agent length and system length was of the same order of magnitude.

5. Results

The flow-density relation of the pedestrian experiment can be divided into three regimes $\rho \in [0, 1.0]$ m^{-1}, $[1.0, 1.7]$ m^{-1} and $[1.7, 3.0]$ m^{-1}, which correspond to three states of pedestrian