UNIVERSALITIES IN FUNDAMENTAL DIAGRAMS OF CARS, BICYCLES AND PEDESTRIANS

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INTRODUCTION

Since the pioneering work of Greenshields the fundamental diagram is used to characterize and describe the performance of traffic systems [1,2]. During the last years the discussion and growing data base revealed the influence of human factors, traffic types or ways of measurements on this relation, see e.g. [3,4] and many others. The manifoldness of influences is important and relevant for applications but moves the discussion away from the main feature characterizing the transport properties of traffic systems. We focus again on the main feature by comparing the fundamental diagram of cars, bicycles and pedestrians moving in a row in a course with periodic boundaries. The underlying data are collected by three experiments, performed under well controlled laboratory conditions [5-9]. In all experiments the setup in combination with technical equipment or methods of computer vision allowed to determine the trajectories with high precision. The trajectories visualized by space-time diagrams show three different states of motion (free flow state, jammed state and stop-and-go waves) in all these systems. Obviously the values of speed, density and flow of these three systems cover different ranges. However, after a simple rescaling of the velocity by the free speed and of the density by the length of the agents the fundamental diagrams conform regarding the position and height of the capacity. This indicates that the similarities between the systems go deeper than expected and offers the possibility of a universal model for heterogeneous traffic systems.

EXPERIMENTS

All three experiments were performed with similar setups, namely on circuits with closed boundary conditions where only single-file motion was allowed. Series of runs were carried out with a maximal number of participants N_{max} = 70, 23 and 33 for the pedestrian, car and bicycle experiment, respectively. To adjust the global density different runs were performed with different numbers of participants N. In general, participants were asked to move normally without overtaking. Details of the experiments could be found in [5,6] for cars, in [7,8] for bicycles and in [9,10] for pedestrian. Time-space diagrams are shown in the center of Fig. 1 and 2. Similar plots for cars can be found in [5]. In all three cases a transition from free flow to jammed flow can be observed when the global density is increased. In the free flow regime all agents can move with their desired speed whereas in the jammed regime stop-and-go waves are observed.

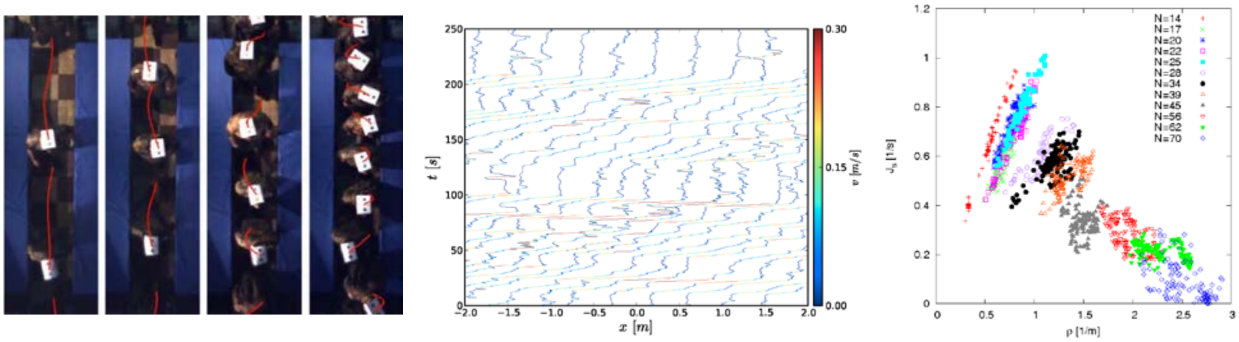

FIGURE 1 Left: Snapshots of the pedestrian experiment at different densities. The red lines show the trajectories determined automatically from video recordings. Center: Trajectories in space and time in the measurement area (of length 4 m) with N = 70. Right: Density – flow relation. Colors indicate data for runs with different N.

On the right of Fig. 1 and 2 the density-flow relations are shown. Details of the measurement method could be found in [8]. The fundamental diagram of pedestrians shows three regimes $\rho \in [0,1.0]\ m^{-1}$, $[1.0,1.7]\ m^{-1}$ and $[1.7, 3.0]\ m^{-1}$ corresponding to three states of pedestrian movement. At the free flow regime ($\rho < 1.0\ m^{-1}$) the flow increases monotonically with the density. For the congested state ($\rho > 1.0\ m^{-1}$) the specific flow starts to decrease with increasing density. For $\rho > 1.7\ m^{-1}$ stop-and-go waves dominate the motion of the pedestrians, see [9,10]. Similar results are observed in the bicycle system [7,8].

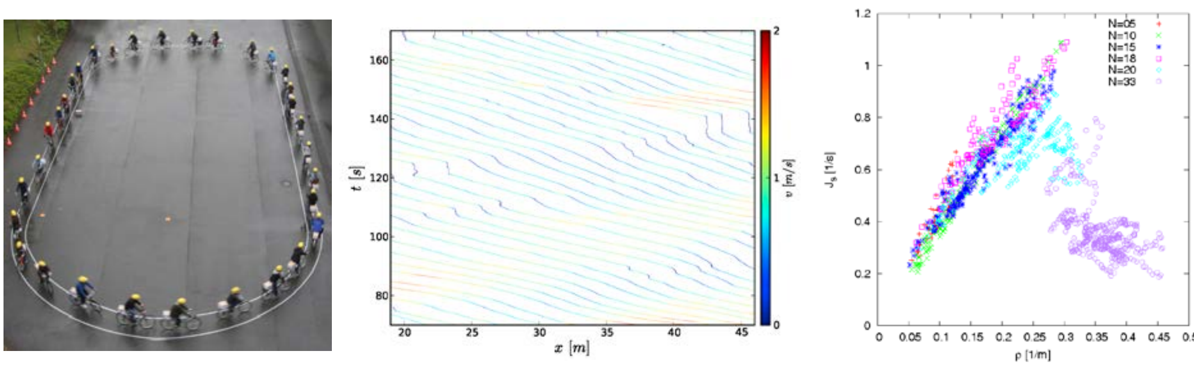

FIGURE 2 Left: Snapshots of the bicycle experiment. Center: Trajectories in the measurement area (of length 27 m) for the bicycle experiment with N = 33. The same structures can be found in trajectories of vehicle systems [5,6]. Right: Density – flow relation. Colors indicate data for runs with different N.

RESULTS

Plotting the fundamental diagram of these three systems in one diagram shows that the data points occupy different ranges of density as well as speeds and do not seem to be comparable to each other, see Figure 3. To take into account the different scales of sizes and speeds of the agents we rescale these quantities. For the length of the agents we use $L_0(p) = 0.4$ m for pedestrians, $L_0(c) = 3.9$ m for cars [6] and the mean value of $L_0(b) = 1.73$ m for bicycles [7,8]. For scaling the speed we used the free flow speed of each agent. From measurements of the free flow speed in special runs of the experiments we know that they are about 1.4 m/s for pedestrians and 5.5 m/s for bicycles. For cars we use 11.1 m/s (about 40 km/h) according to [6].

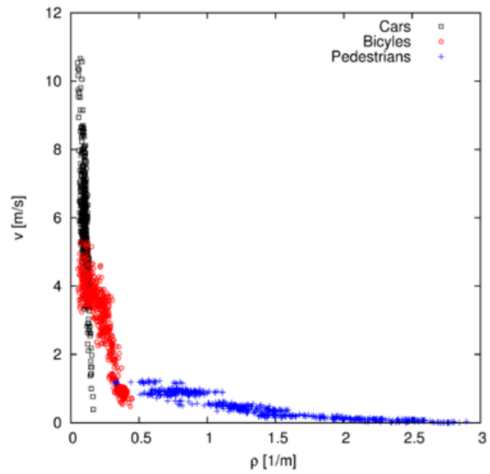

FIGURE 3 Fundamental diagrams for cars, bicycles and pedestrians. Raw data of the density-speed relation.

After rescaling it is found that the fundamental diagrams agree and in all three cases the free flow regimes ends at approximately $\rho^*L_0 = 0.5$, see Figure 4. This implies that the transition to the congested state occurs when nearly 50% of the available space is occupied. Moreover, the capacity, i.e. the maximal flow, agrees for the three systems after the rescaling and amounts 0.25 to 0.30. In the congested regime the slopes of the fundamental diagram are again similar for all three systems.

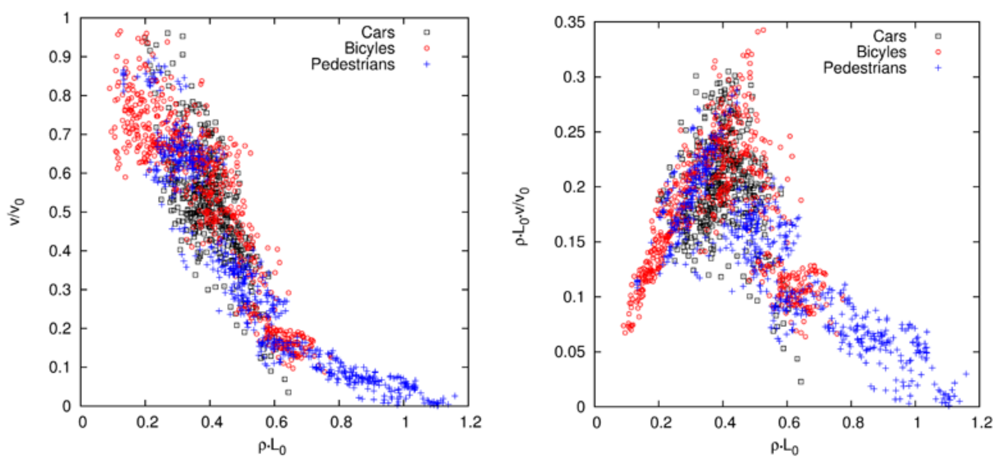

FIGURE 4 Fundamental diagrams for cars, bicycles and pedestrians. Left: Scaled data of the density-speed relation. Speed and density rescaled with the free speed v_0 and the length of the agents L_0. Right: Scaled density-flow relation. After the scaling the fundamental diagrams agree in the density range observed.

The transport properties in such systems could be approximated by the universal equation $\tilde{v} = 1 - \tilde{\varrho}$ with $\tilde{v} = v/v_0$ and $\tilde{\varrho} = \varrho L_0$. The normalized maximal flow is then 0.25 at a relative density of 0.5. This corresponds to the properties to the ASEP [11,12] which is for a long time considered as a minimal model for traffic flows. The main feature of this model is volume exclusion. Also models for pedestrian dynamics [13-15] show that these transport characteristics could be reproduced by an appropriate consideration of a velocity dependent volume exclusion, which seems to be a universal characteristics of such systems. Considering this universality we conclude that other properties of the agent, like acceleration or inertia are less relevant for the structure of the fundamental diagram in single file traffic systems of different agent types. In other words models without a proper consideration of the volume exclusion miss an important aspect of traffic systems.

REFERENCES

[1] Greenshields, B. D. The Photographic Method of studying Traffic Behaviour. Proceedings of the 13th Annual Meeting of the Highway Research Board, 1933.

[2] Greenshields, B. D. A study of highway capacity. Proceedings Highway Research Record, Washington Volume 14, 1935, pp. 448-477.

[3] Coifmann B. Jam Occupancy and Other Lingering Problems with Empirical Fundamental Relationships, TRB 2014 Annual Meeting, Memorystick, 14-0032

[4] Hranac R., E. Sterzin, D. Krechmer, H. Rakha, and M. Farzaneh. Empirical Studies on Traffic Flow in Inclement Weather. Federal Highway Administration. Report Number: FHWA-HOP-07-073, October 2006.

[5] Sugiyama, Y., M. Fukui, M. Kikuchi, K. Hasebe, A. Nakayama, K. Nishinari, S. Tadaki, and S. Yukawa. Traffic jams without bottlenecks - Experimental evidence for the physical mechanism of the formation of a jam. *New Journal of Physics*, Vol. 10, 2008, p. 033001.

[6] Tadaki, S., M. Kikuchi, M. Fukui, A. Nakayama, K. Nishinari, A. Shibata, Y. Sugiyama, T. Yosida, S.Yukawa. Phase transition in traffic jam experiment on a circuit, *New Journal of Physics*, Vol. 15, 2013, p. 103034

[7] Andresen E., M. Chraibi, A. Seyfried, F. Huber, Basic driving dynamics of cyclists. In: Proceedings of the conference ‘Simulation of Urban Mobility 2013’, Behrisch M., M. Knocke, D. Krajzewicz (Eds), *Lecture Notes in Computer Science (LNCS)*, Springer, 2014, in print.

[8] Zhang, J., W. Mehner S. Holl M. Boltes, E. Andresen, A. Schadschneider, A. Seyfried. Universal flow-density relation of single-file bicycle, pedestrian and car motion. Submitted to *New Journal of Physics*, 2014

[9] Seyfried, A., M. Boltes, J. Kähler, W. Klingsch, A. Portz, T. Rupprecht, A. Schad-schneider, B. Steffen, A. Winkens. Enhanced empirical data for the fundamental diagram and the flow through bottlenecks. In: *Pedestrian and Evacuation Dynamics 2008*, Springer, 2010, pp. 145-156

[10] Seyfried, A., A. Portz, and A. Schadschneider, Phase coexistence in congested states of pedestrian dynamics. In: Bandini, S., S. Manzoni, H. Umeo, G.Vizzari (Eds.), *Cellular Automata*, Springer, 6350, 2010, pp. 496-505

[11] Derrida B., An exactly soluble non-equilibrium system: The asymmetric simple exclusion process, *Phys. Rep.* 301, 65, 1998

[12] Schadschneider, A., D. Chowdhury, and K. Nishinari. *Stochastic Transport in Complex Systems: From Molecules to Vehicles*, Elsevier, 2010

[13] Seyfried, A., B. Steffen, and T. Lipper., Basic of modeling the pedestrian flow, *Physica A*, 368, 232-238, 2006

[14] Chraibi, M., A. Seyfried, and A. Schadschneider. Generalized centrifugal force model for pedestrian dynamics, *Phys. Rev. E*, 82, 046111, 2010

[15] Kirchner, A., H. Klüpfel, K. Nishinari, A. Schadschneider, and M. Schreckenberg. Discretization effects and the influence of walking speed in cellular automata models for pedestrian dynamics, *J. Stat. Mech.* 10, P10011, 2004