TRAFFIC FLOW FROM A PHYSICS PERSPECTIVE

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Physicists have been interested in traffic for a long time for various reasons. On the one hand, we all participate in traffic as pedestrians or drivers. On the other hand, traffic systems exhibit interesting, and sometimes counter-intuitive, collective phenomena. They are examples for nonequilibrium systems which allows to apply and test methods developed in statistical physics.

Meanwhile they are an important facet of active matter systems, notably because they are macroscopic systems for which extensive data is available. On the practical side there is hope that efficiency and safety in traffic can be improved when underlying mechanisms are better understood.

The interest of physicists in traffic goes back to the 1950ies. Well-known researchers like R.B. Potts have made important contributions and I. Prigogine even wrote a book ("Kinetic Theory of Vehicular Traffic" with R.C. Herman) about the application of statistical mechanics to traffic. Currently pedestrian and crowd dynamics has become the focus of attention, not at least due to several crowd disasters reported in the media. Pedestrian dynamics is more challenging than vehicular traffic where the behavior is strongly restricted by traffic rules (lanes!) and physics (inertia!) and can mostly be considered as (quasi-)one-dimensional. In pedestrian motion, agents move in different directions, *i.e.*, the motion is generically two-dimensional, while at the same time direction of motion and speed can change almost instantaneously.

Vehicular traffic

The arguably most important quantity in every traffic system is the fundamental diagram. It depicts the dependence of traffic flow (or current, in physics terminology) on vehicle density. The typical form is shown in Fig. 1. Two different regimes can be distinguished. For small densities the flow increases linearly with density. The slope in this free flow regime is given by the desired velocities of the drivers, *e.g.*, a speed limit. All cars can move at maximal allowed velocity and interactions are rare. For higher densities the flow decreases with increasing density. In this jammed (or congested) regime interactions become relevant and lead to the formation of jams. The dominating driver behavior here is the avoidance of accidents.

The fundamental diagram exhibits a fundamental dilemma. Drivers prefer small densities where one can drive as fast as possible. However, traffic engineers want to optimize flow, but the largest flow (typically larger than 2000 vehicles/h) is reached typically at some finite density ρ_c = 25-30 vehicles/km.

A familiar collective phenomenon are "phantom traffic jams" (Fig. 2). They appear to have no obvious reason like accidents, road construction or lane reduction. Therefore, they should not exist since all drivers try to move as fast as possible! What is their origin then? The consensus is that these jams are caused by a chain reaction triggered by driving imperfections. A fast driver approaching a slower car brakes to avoid an accident, thereby reducing velocity more than necessary. This triggers further braking maneuvers of following cars. If the density is sufficiently high a chain reaction ensues which finally can force

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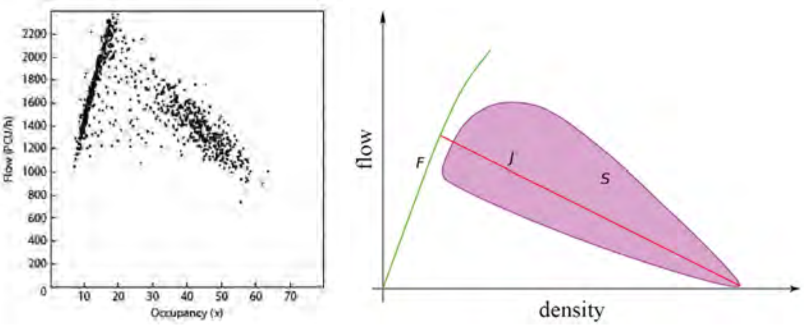
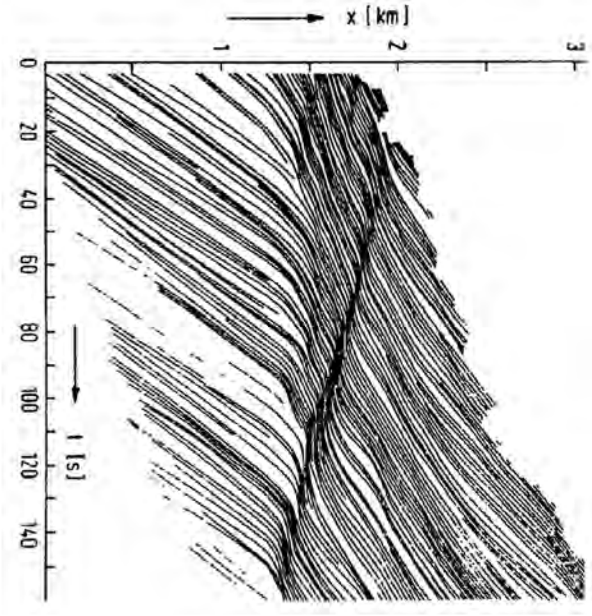


▲ **FIG. 1: Left:** Empirical fundamental of a Canadian highway. Each point corresponds to an average over 5 minutes. At small densities, the flow increases linearly (free flow) whereas at higher densities it decreases with increasing density. **Right:** Schematic fundamental diagram. The free flow, jammed and synchronized phases are indicated by "F", "J" and "S", respectively.



▸ **FIG. 2:** Empirical trajectories showing formation of a phantom traffic jam. The jam front moves at constant velocity oppositely to the driving direction.

● ● ● a car to stop. Ironically the driver responsible for the formation of this jam will not even notice! Therefore, there is no incentive to change behavior. This mechanism has been not only been observed on real highways (Fig. 2), but also in controlled experiments.

Although spontaneous traffic jams have been observed in many different systems, there is one notable exception, namely ant trails. Using pheromones, many ant species create a road network that has strong similarities with human-build highways. However, they are able to avoid spontaneous jam formation even at extremely high densities.

A closer look exhibits additional features of the fundamental diagram. In a density interval near ρ_c the flow may not be uniquely determined by the density. The states with higher flow are not stable and can decay into jammed states under perturbations. For densities beyond ρ_c the measurement data show a strong scattering (Fig. 1). This has been associated with a new phase, termed somewhat misleadingly "synchronized traffic". Here the desire for driving comfort determines the behavior, *e.g.*, avoiding abrupt changes in speed, which leads to the formation of platoons of cars moving at similar velocities. Depending on the structure of the platoons and their speed, different flows can be realized and no functional relationship between flow and densities exists.

What can we do?

Will new technology help to reduce traffic problems? Historically, the main cure for traffic congestion was building new roads or expanding existing ones. This is usually not very effective in the long-term, which is known as *Paradox of Traffic or Downs-Thomson Paradox*. New or expanded roads are attractive at first because congestion and travel times are reduced. This creates new demand. Using the car becomes more attractive and eventually the increased demand will lead to similar congestion levels than before.

Braess Paradox describes the counter-intuitive situation when improving the capacity of a network by new fast roads leads to an overall increase of travel times. Since drivers try to minimize their travel time this quickly leads to congestion of the new road. This is different from the Downs-Thomson Paradox which is based on the increase of the overall demand whereas in Braess Paradox the demand is only redistributed. Braess' Paradox also occurs in other transportation networks, like power grids, and physical systems such as mechanical or electrical networks.

Meanwhile modern cars are equipped with many sensors and driver-assistance systems, like *Adaptive Cruise Control* (ACC). ACC systems can adjust the velocity automatically according to the traffic situation, *e.g.*, based on the distance to the car ahead. This not only improves safety, but helps to avoid chain reactions leading to jams as ACC systems are able to adjust speed much more precisely than a human driver. Thus, it will help to reduce the number of jams, even if not all vehicles are equipped with ACC. Already a market penetration of 20% will reduce the number of jams and accidents substantially.

Such systems are even more effective when combined with *Car-To-X communication* which connects cars with other cars and infrastructure like traffic signals. Then information about the traffic situation ahead can be transmitted by cars moving in the opposite direction. Up-to-date information is already provided on webpages based on data from counting loops and computer simulations to interpolate the state at locations without detectors. www.verkehr.nrw displays the current state of the Autobahn network of North Rhine-Westphalia where the simulations also provide predictions for the evolution of the state within the next hour.

In contrast to weather forecasts, traffic forecasts become invalid when made publicly available. Users might change their travel decision, *e.g.*, by choosing a different route or starting time, or even use a different mode of transport. This is currently the main obstacle for reliable traffic forecasts! One has to understand in more detail how users react to predictions.

Pedestrian and crowd dynamics

Nowadays the physics of vehicular traffic seems well understood and besides some details there is consensus about the relevant mechanisms even on a quantitative level. This is rather different for the dynamics of pedestrian crowds which have become a focus of attention. Pedestrian dynamics is more complex than vehicular traffic for several reasons. The motion is genuinely two-dimensional with agents moving in different directions. Additionally, it is not strongly restricted by traffic rules, but conventions and habits which might depend on cultural background *etc.* This makes the description of crowds more challenging, but also more interesting. It leads to several new collective phenomena not observed in vehicular traffic, *e.g.*, the dynamic formation of lanes in pedestrian streams that move in opposite directions (Fig. 3).

Several crowd disasters in recent years have shown that a better understanding of pedestrian dynamics is needed. It will help to improve not only safety in public areas or large-scale event, like music festivals or sports events, but also comfort. In order to develop models for planning of events, optimization of evacuation strategies reliable quantitative data is needed. In contrast to the situation in vehicular traffic, where accurate data can be obtained *e.g.*, using counting loops, field observations of pedestrian motion are much more difficult. Therefore, laboratory experiments have become an important tool. Experiments with up to 1000 test persons have been performed in simple, but characteristic scenarios, *e.g.*, corridors, bottlenecks *etc.* (Fig. 3). The data is used to validate and calibrate models which than allows to make quantitative predictions even in more complex scenarios based on computer simulations. This close interplay between experiment and theory has been established not least due to the influence of physicists active in the field.

Laboratory experiments help to improve legal guidelines for mass events. For quite some time even simple scenarios were not fully understood, *e.g.*, how the flow through a corridor varies with its width. Two competing results were both used as basis for guidelines in different countries. One assumed a linear increase of flow with width whereas the other predicted, based on lane formation, a stepwise increase. Experiments showed that the flow indeed increases continuously which is now used *e.g.* in all German guidelines.

For the fundamental diagram there is still no consensus on a quantitative level. Experiments show large differences *e.g.*, in the maximal flow or the critical density. Several influencing factors have been identified (density definition, cultural background of test group, psychological effects,...), but a full understanding is still missing.

As an application, so-called evacuation assistants are developed, *e.g.*, for evacuations of sports arenas. Empirical data for the distribution of spectators in the stadium and information about the availability of exit routes are used to perform faster-than-real-time computer simulations of an evacuation in these circumstances. This information is provided to the decision makers (safety personal, fire fighters,...) allowing them to redirect pedestrian streams to avoid crowding at critical points which is a considerable safety risk.

Outlook

The physics of vehicular traffic is rather well understood. Currently models are used to investigate the effects of CAV, Car2X communication *etc.* which (hopefully) not too far in the future will lead to a substantial reduction of congestion and accidents. For pedestrian dynamics, there are still several open problems. This is partially related to the problems in acquiring accurate empirical data, but also due to the relevance of psychological aspects as pedestrian motion is much less determined by physics than vehicular motion (small inertia effects).

Besides human traffic, other biological traffic-like systems show interesting new features. Ants are able to avoid spontaneous jams, but also intracellular transport by molecular motors has attracted a lot of interest, not at least through possible connections with diseases like Alzheimer's or ALS. Therefore, there is still a lot to do in this fascinating field. ■

About the Author

Andreas Schadschneider has obtained his Ph.D. in 1991 working in theoretical solid state physics. He is professor at the Institute for Theoretical Physics and the Institute for Physics Education of the University of Cologne. His main research interests are related to the fundamental physics underlying all kinds of traffic systems (vehicles, pedestrians, biological systems,...)

▼ **FIG. 3:** Pedestrian experiments: **Left:** flow through a bottleneck; **Right:** lane formation in counterflow. The white hats are needed for automated tracking of the pedestrians when extracting the trajectories from video.