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Traffic jams without bottlenecks—experimental evidence for the physical mechanism of the formation of a jam

Yuki Sugiyama[1,10], Minoru Fukui[2], Macoto Kikuchi[3], Katsuya Hasebe[4], Akihiro Nakayama[5], Katsuhiro Nishinari[6,7], Shin-ichi Tadaki[8] and Satoshi Yukawa[9]

[1] Department of Complex Systems Science, Nagoya University, Nagoya 464-8601, Japan
[2] Nakanihon Automotive College, Sakahogi 505-0077, Japan
[3] Cybermedia Center, Osaka University, Toyonaka 560-0043, Japan
[4] Aichi University, Miyoshi 470-0296, Japan
[5] Faculty of Science and Technology, Meijo University, Nagoya 468-8502, Japan
[6] Department of Aeronautics and Astronautics, The University of Tokyo, Bunkyo 113-8656, Japan
[7] PRESTO, Japan Science and Technology Agency
[8] Computer and Network Center, Saga University, Saga 840-8502, Japan
[9] Department of Earth and Space Science, Osaka University, Toyonaka 560-0043, Japan
E-mail: sugiyama@phys.cs.is.nagoya-u.ac.jp

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Abstract. A traffic jam on a highway is a very familiar phenomenon. From the physical viewpoint, the system of vehicular flow is a non-equilibrium system of interacting particles (vehicles). The collective effect of the many-particle system induces the instability of a free flow state caused by the enhancement of fluctuations, and the transition to a jamming state occurs spontaneously if the average vehicle density exceeds a certain critical value. Thus, a bottleneck is only a trigger and not the essential origin of a traffic jam. In this paper, we present the first experimental evidence that the emergence of a traffic jam is a collective phenomenon like 'dynamical' phase transitions and pattern formation

[10] Author to whom any correspondence should be addressed.

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in a non-equilibrium system. We have performed an experiment on a circuit to show the emergence of a jam with no bottleneck. In the initial condition, all the vehicles are moving, homogeneously distributed on the circular road, with the same velocity. The average density of the vehicles is prepared for the onset of the instability. Even a tiny fluctuation grows larger and then the homogeneous movement cannot be maintained. Finally, a jam cluster appears and propagates backward like a solitary wave with the same speed as that of a jam cluster on a highway.

Why do traffic jams appear on highways? The phenomenon occurs every day, but the reason has been poorly understood. We often encounter a jam even if we have no apparent reasons such as traffic accidents or construction. It is commonly understood that such a jam appears near a 'bottleneck', for example, on-ramps, tunnels and sags.

In the 1990s, a new physical concept was introduced into research on traffic flow [1]–[4]. That is, traffic flow is investigated as a dynamical phenomenon of a many-particle system. In general, such a system drastically changes its macroscopic aspect owing to the effect of the collective motion of interacting particles. Such phenomena are observed in several fields in physics. The characteristic features of collective phenomena are phase transition, bifurcation of a dynamical system, pattern formation, etc. It is not unexpected that the same physical mechanism appears in socio-dynamical objects. Traffic jams are just the subject for investigation along this line. We have succeeded in simulating a traffic jam by mathematical models without a bottleneck, whenever the average vehicle density on the road exceeds a certain critical value [2]–[4]. The crucial point is the effect of collective motion caused by the interaction among vehicles, which is originated by drivers seeing other vehicles. The effect makes the free flow unstable and generates a traffic jam similar to phase transitions and pattern formation in non-equilibrium many-particle systems.

Can our mathematical prediction be tested? In this paper, we report the first experimental verification that a jam can be generated in the absence of a bottleneck. Our experimental result is consistent with our simulations, and provides clear evidence that the emergence of a jam is a collective phenomenon.

In real data, the relationship between vehicle density and flow rate (fundamental diagram) has a universal property in highway traffic (figure 1). The data points of traffic flow are sharply divided into two parts at the critical value of the vehicle density, labelled as free flow and congested traffic flow. In the congested flow part, it is easily supposed that a traffic jam appears just beyond the critical density. Fundamental diagrams show similar shapes at any point on any highway, and the critical density is almost the same value. Such common properties indicate that the phenomenon of traffic jams can be studied from the physical point of view as a dynamical phase transition.

On highways, a driver controls a vehicle so as not to collide with the vehicle in front, meaning that a vehicle slows down at a short headway distance. This behavior is essential for describing the phenomena of traffic flow. Thus, we treat the vehicles as particles moving collectively with an interaction such that each changes its velocity on seeing the preceding vehicle to avoid collision. Mathematical models of traffic flow are constructed focusing on this simple property of the motion of vehicles. In short, traffic flow is a non-equilibrium physical system consisting of moving particles with asymmetric interaction of exclusive effect. The models have basically two kinds of solutions: a free flow solution and jam flow solutions. In

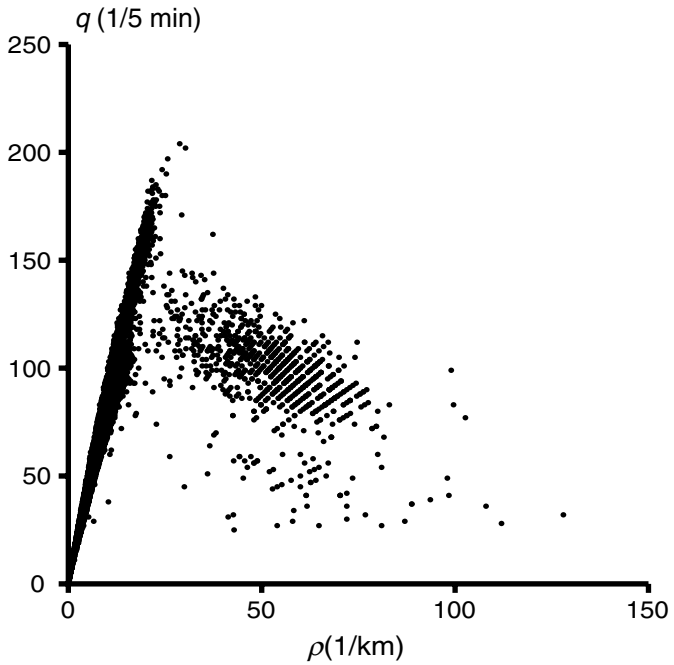

Figure 1. The typical fundamental diagram (the relation between vehicle density and flow rate) from 1 month of data measured at a point on a freeway. The critical density is nearly 25 (vehicles km^{-1}). The data were measured by the Japan Highway Public Cooperation.

a free flow solution, all vehicles move at nearly the same large velocity with a safe distance between two successive vehicles. In contrast, a jam flow solution shows traveling clusters in a flow. Vehicles almost stop in a cluster, which is identified with a traffic jam. Such models have succeeded in forming a jam on a circuit in the absence of a bottleneck, when a free flow is initially set and the average vehicle density is a little bit larger than a certain critical value, which corresponds to the critical density of fundamental diagrams [4]–[10][11,12].

The physical mechanism of forming a jam is summarized as follows. Small fluctuations always exist in the movement of vehicles in a traffic flow. If the vehicle density is low, such a fluctuation disappears and the free flow is maintained. On the other hand, if the density exceeds the critical value, the fluctuation cannot disappear but instead grows steadily and eventually breaks the free flow. After relaxation, a jam is created and travels along the circuit without decaying. Mathematically, the free flow solution is unstable and the jam flow solutions become stable. The stability change at the critical density caused by the enhancement of fluctuations in a free flow is understood as a phase transition of non-equilibrium systems. The phenomenon originates from the dynamical effect of the collective motion in a many-body system. It does not require the existence of a bottleneck.

The mechanism works in a real traffic flow. Here, we describe an experiment that confirms our mathematical studies, under the same environment consistent with our simulation [4]. We believe that our experiment clearly eliminates the existing prejudice about the origin of a jam,

[11] www.traffic-simulation.de
[12] http://traffic.phys.cs.is.nagoya-u.ac.jp/~mstf/index_e.html

Figure 2. A snapshot of the experiment on a circular road. The circumference is 230 m, and the number of vehicles is 22. A 360-degree video camera is situated at the center of the circle for measurement.

that is, a jam appears only near a bottleneck. We reveal the essential origin of jam formation from the physical point of view.

We perform the experiment using a circular road in a homogeneous lane condition on flat ground. The setting corresponds to the situation of the mathematical simulations[13,14]. A snapshot of the experiment is shown in figure 2. We set a queue of vehicles moving along the circular road. A sufficient number of vehicles are put onto the circular road so that the density satisfies the condition for the onset of the instability of free flow, which is estimated by a mathematical model [4, 12]. The circumference is 230 m, and the number of vehicles is 22. A 360-degree video camera was set at the center.

Before starting the experiment, the vehicles were tuned so that they cruise along the circular road at the same velocity ($\sim$30 km h^{-1}) with almost uniform spacing. The drivers were requested to cruise at about 30 km h^{-1}. The velocity seems to be high considering the average headway distance. We need an appropriate velocity for cruising in order to satisfy the unstable condition for homogeneous motion in our situation. We can identify the motion of the queue of vehicles with a free flow. Then, the experiment started. The drivers are only instructed to follow the vehicle ahead in safety in addition to trying to maintain their cruising velocity. We provide two supplementary movies of the experiment, available from stacks.iop.org/NJP/10/033001/mmedia. A bird's-eye view of the experiment is seen in movie 1 and movie 2 shows a view from the 360-degree camera. In the initial stage, the free flow is maintained for a while (figure 3(a)). After some time, small fluctuations appeared in the headway distances and developed as time progressed. It takes a period of time for the fluctuations to grow enough to break down the free flow. The free flow has been disturbed and the vehicles cannot move homogeneously any more. Finally, several vehicles are forced to stop completely for a moment (figure 3(b)). A clear 'stop-and-go wave' is observed, and furthermore,

[13] Circular road experiments were done by some traffic engineers many years ago. But their purpose and interest are completely different from ours. See for example [11].

[14] The preliminary performance was done for a science TV program supported by some members of our group in 2000. The plan was provided by M Bando, M Kikuchi, A Nakayama, K Nakanishi and Y Sugiyama.

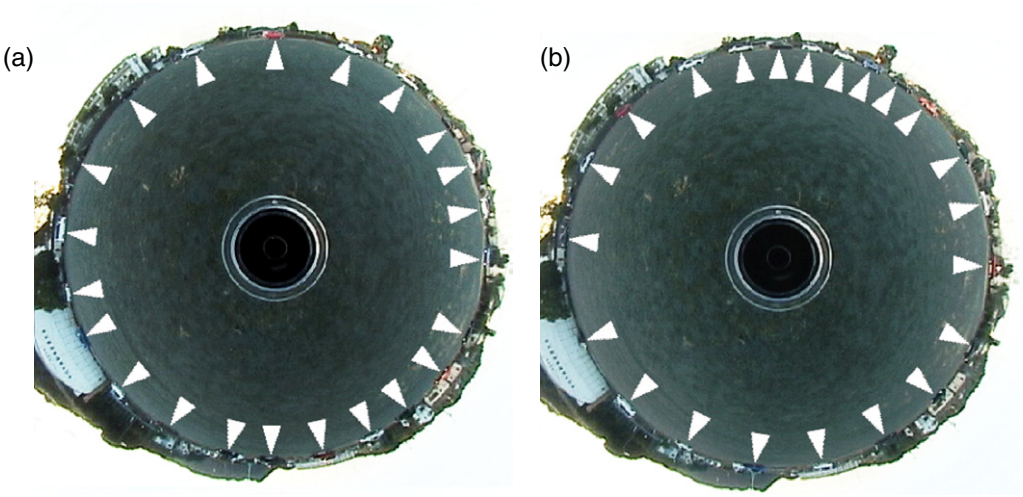

Figure 3. The vehicles move along the circle. The pictures are taken by the 360-degree video camera. We show the position of each vehicle by a triangle: (a) The snapshot at the initial stage shows that the vehicles move as the free flow. (b) The snapshot 3 min later shows that a jam has been formed. A jam consists of five vehicles, which is seen at the top of the circle at this moment. This picture corresponds to figure 2. (A jam is observed on the upper right corner of the circle.)

it propagates in the opposite direction to the movement of vehicles, which is nothing but a jam. The jam cluster moves as a solitary wave and maintains its size and velocity (figure 4).

We observed the instability of free flow on the circular road and the emergence of a traffic jam with no obstacle or bottleneck. The vehicles inside the cluster of the jam stop completely, and the vehicles outside move freely ($\sim$40 km h^{-1}). The vehicle at the front of the cluster starts to accelerate and escapes from it, while another vehicle reaches the back of the cluster. The repetition of such a movement preserves the stability of the cluster, and the cluster itself travels backward with a velocity of roughly 20 km h^{-1}—the common value of the velocity of a jam measured on real highways (figure 5) [13]–[15]. The essential property of a jam is determined by the movement. As a result, the backward velocity of a jam cluster is not affected whether the length of the cluster is long or short. Although the emerging jam cluster in this experiment is small (five vehicles), its behavior is not different from large ones on highways.

The essence of the instability in highway traffic can be realized in our experiment. The conditions for the velocity and headway seem to be hard for drivers, because the length of the circuit is short. If we had used a longer circuit, the experiment could have been performed much more easily. We performed several experiments with different numbers of vehicles. In the case of 23, a jam cluster was formed and its velocity was the same as the case of 22[15].

The mechanism of the formation of a jam in the practical situation on highways is explained basically by a similar scenario to the experiment on a circular road. Suppose an open system such as a straight road. When a large number of vehicles, beyond the road capacity, are successively injected into the road, the density exceeds the critical value and the free flow state becomes unstable. The situation is the same as the setting of the experiment. In this situation,

[15] More detailed discussions on the results of the experiments and the range of density for instability will be presented in our forthcoming papers and future experiments.

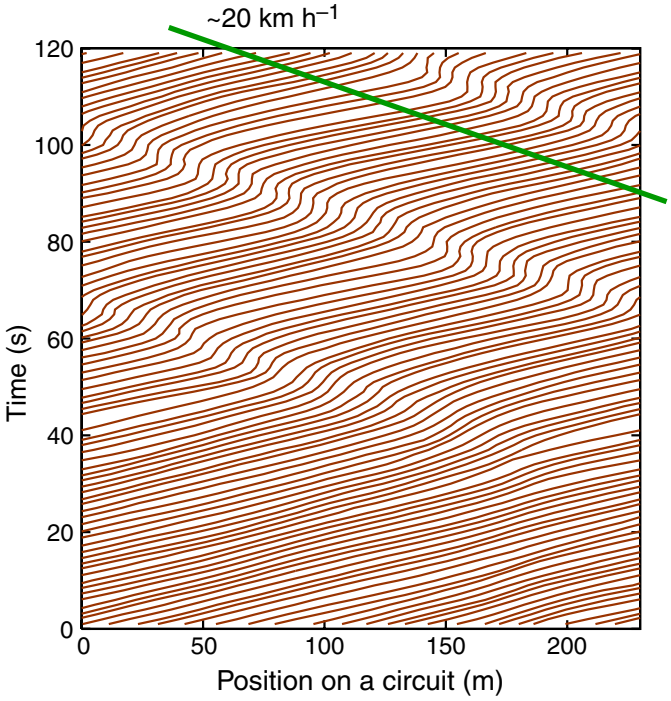

Figure 4. The traces of individual vehicles on the circular road (0 m-point is identical to 230 m-point) in the period of 2 min during the emergence of a jam. The data are captured from the movie taken by the 360-degree video camera (for example, pictures in figure 3). The jam cluster is clearly observed and it moves backward at a velocity of roughly 20 km h^{-1} and maintains its motion.

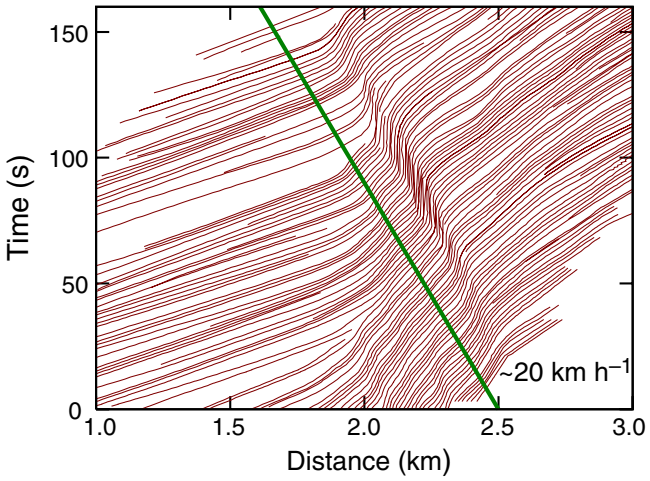

Figure 5. The traces of individual vehicles on the highway in an aerial photograph taken in 1967 by Treiterer and Myers [14]. (The curves are traced from figure 1 of [14].) The green line representing a backward velocity of 20 km h^{-1}, which corresponds to the velocity of the jam cluster in our experiment, is added as a reference.

some perturbation breaks the free flow and its state transits to a jam flow state, just as the enhancement of fluctuations does in the case of our experiment. In any case, the instability of a free flow caused by exceeding the critical density leads to the transition to a jamming state by the collective effect of vehicles such as the enhancement of fluctuations or some perturbation. Actually, the emerging jam on a circular road has just the same property as that observed upstream of a bottleneck on highways.

We have shown that the emergence of a traffic jam really occurs in the absence of a bottleneck. A jam is generated spontaneously only if the average vehicle density exceeds the critical value. Under this condition, the free flow state is unstable and even a tiny fluctuation grows and the state transits to jamming phase by the effect of collective motion. Thus neither an apparent obstacle nor a bottleneck is needed for the formation of a jam. However, it is commonly believed that a bottleneck causes a traffic jam. Actually, it seems this way because a bottleneck increases the density and makes the density exceed the critical value. The condition is simply realized on a circular road, because the density can be fixed beyond the critical value just as in our experiment. In conclusion, jam formation is an effect of the collective motion in the physics of a non-equilibrium phase transition of a many-particle system. The emergence of a jam with no bottleneck provides proof of the essential mechanism of the formation of a jam.

Acknowledgments

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