Experimental Properties of Phase Transitions in Traffic Flow

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Investigations of a great number of measurements of traffic flow on German highways show that there are some common macroscopic properties of phase transitions between free flow, synchronized flow, and traffic jams. In particular, it is shown that a short-time localized perturbation is able to cause a local phase transition from free flow to synchronized flow and that synchronized flow of slow moving vehicles can further be self-maintained on a highway for several hours. [S0031-9007(97)04491-8]

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Critical phenomena and phase transitions are the fundamental properties of a huge number of physical systems. Phase transitions may also occur in traffic flow when the density of vehicles exceeds some characteristic value. Treiterer, in particular, has experimentally proved that a traffic jam can spontaneously appear without obvious reasons in free traffic flow and that the appearance of the jam is accompanied by a hysteresis phenomenon [1]. Recall that a jam is a localized region of very high density of vehicles in traffic, where vehicles either cannot move at all or where every vehicle comes to a brief stop inside a jam. However, in experiments traffic flow shows a very complex time-space behavior [2,3]. The occurrences of jams in free flow therefore can be expected to not be the single type of phase transitions. Indeed, it has recently been found out experimentally [4] that the complexity in traffic flow is linked to diverse space-time transitions between three basically different kinds of traffic: (i) Free traffic flow, where vehicles are able to change a lane and to pass, (ii) synchronized traffic flow, where vehicles are not able to pass due to a higher density as in free flow, and (iii) jams. In this article the experimental macroscopic properties of phase transitions in traffic flow will be presented.

Between 1991 and 1997 phase transitions between free flow, synchronized flow, and jams on the German highways A5 and A44 have been investigated on different days. Since it has been found out that the macroscopic properties of these phase transitions are similar in all cases, it is sufficient to consider only one morning on Wednesday, 13 September 1995 on a section of the highway A5 between Bad Homburg and Frankfurt [Fig. 1(a)] as a representative data set. In this data set during the time between 6:43–10:43 all kinds of traffic (free flow, synchronized flow, and a jam) occur. Consequently, we are faced with different types of transitions between these kinds of traffic [Figs. 1(b) and 1(c)]. The considered section of the highway has two intersections with other highways (I1, “Bad Homburger Kreuz” and I2, “Nordwestkreuz Frankfurt”) and is equipped with ten sets of induction loop detectors (D1, ..., D10). The sets D1, D2, and D10 are situated inside the intersections I1 and I2, correspondingly. Each of them consists of four detectors for a left (passing), a middle, and a right lane, plus one for the acceleration lane related to on-ramps (at D2) or to off-ramps (at D1 and D10). Vehicles moving in the acceleration lane squeeze on to the highway approximately 200 m downstream from the detector at D2 [Fig. 1(a)]. The other sets of detectors (D3–D9) are situated on the three-lane road without on- and off-ramps, where each of them thus consists of three detectors only. The induction loop detector records the crossing of a vehicle and measures its crossing speed. A local road computer produces sequences of pulses for each lane of the road for the flux q and for the average speed v of vehicles crossing the detector during a one minute interval. Besides, the computer provides information about the dispersion of the speed of vehicles and the percentage of long vehicles.

The dependencies of the average speed of vehicles and the flux shown in Figs. 1(b) and 1(c) are related to morning rush hours. It is easy to see that due to a high traffic volume, even outside a jam ($7{:}41 < t < 7{:}48$) vehicles move only with fairly low speed during 7:40–9:30 in comparison with either earlier or later time. Note that the basically same behavior is observed on highways in other countries (e.g., [2,3]). On the flux-density plane the free flow (at $t < 7{:}40$ and $t > 9{:}30$) and synchronized flow (at $7{:}40 < t < 9{:}30$) without the jam are basically the same as shown in [4] for the same section of the highway but in the opposite direction. Abrupt changes in the average speed of vehicles can be observed during the transitions from free to synchronized flow (at $t = 7{:}40$) as well as backwards from synchronized flow to free flow (at $t = 9{:}30$). The other properties of synchronized flow shown in Fig. 1 are also the same as in [4]. Apart from that, further investigations of experimental data show that the speed variance which is linked to fluctuations in synchronized flow is considerably lower than in free flow. The latter circumstance may be linked to a bunching of vehicles in synchronized flow which restricts the speed variance between neighboring vehicles. The transition from free flow to synchronized flow which can be clearly

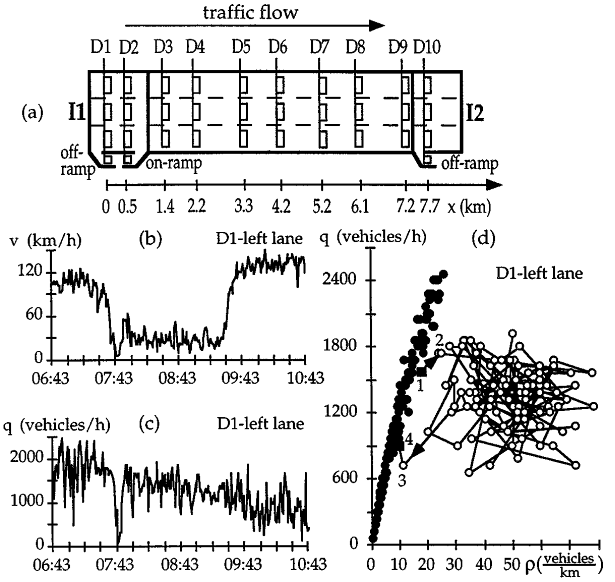

FIG. 1. Transitions between free and synchronized traffic flow at the detectors D1: (a) schematic configuration of the chosen section of the highway A5-South. (This is the opposite direction considered in [4,5].) (b),(c) Characteristic dependencies of the average speed of vehicles (b) and of the flux (c) during rush hours. (d) Free flow (black points) and synchronized flow (circles) on the flux-density plane. The solid lines and arrows in (d) show the transferences between experimental points 1, 2 and 3, 4 which correspond to the time 7:35, 7:36 and 9:29, 9:30.

observed at $t = 7{:}40$ in Figs. 1(b) and 1(d) is in reality *not the phase transition* in traffic flow which is initially responsible for the sharp decrease in the speed of vehicles at D1 [Fig. 1(a)]. To demonstrate this and to investigate the phase transition in traffic flow, one needs to go into more detail concerning the *time-spatial* distributions of the flux and the average speed of vehicles on the whole section of the road during intervals of time when the phase transitions may occur (Fig. 2).

Looking at Figs. 2(a)–2(d) it can be seen that the phase transition from free flow to synchronized flow occurs at $t \approx 7{:}16$ in a vicinity of the detectors D3. It is indeed true because transitions from free to synchronized flow at the detectors D2 ($t = 7{:}22$) upstream and D4 ($t \approx 7{:}17$) downstream from the detectors D3, appear *later* than at the detectors D3 [Figs. 2(a), 2(b), and 2(d)]. Note that although the average speed of vehicles sharply decreases during the phase transition from free flow to synchronized flow, the flux does not change considerably [Fig. 2(e)].

The phase transition from free flow to synchronized flow at $t \approx 7{:}16$ in the vicinity of the detectors D3 causes two different effects:

(i) The appearance of a wave of *induced transitions* from free flow to synchronized flow upstream. This process of induced transitions can explain the transitions from free to synchronized flow measured later at the detectors D2 and D1 [Figs. 2(b) and 2(c)]. From further

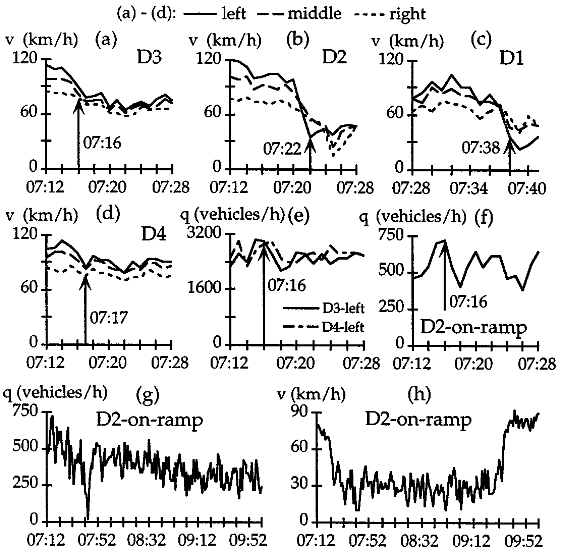

FIG. 2. The phase transition from free flow to synchronized flow: the distributions of the average speed of vehicles for the different (left, middle, and right) lanes of the highway at the detectors D3 (a), D2 (b), D1 (c), D4 (d) and of the fluxes on the left lanes at the detector D3 and D4 (e) in the time interval when the phase transition occurs. (f)–(h) The distributions of the flux (f), (g) and of the average speed of vehicles (h) on the acceleration lane leading to the on-ramp.

investigations of the empirical data, it follows, that this upstream propagation of the wave induced transitions is a nonstationary process. Apparently, the velocity of this wave depends on the flux upstream which noticeably changes in time.

(ii) An appearance of a *propagating synchronized flow* downstream from the location where the phase transition occurred. The propagating synchronized flow supplants free flow downstream. This may explain the transition to synchronized flow measured at the detectors D4 [Fig. 2(d)]. Because vehicles move on the section of the road between the detectors D3–D10 without any hindrance, they are able to accelerate during this propagating process. Therefore, the process of the propagating of synchronized flow causes a *gradual spatial transition* from synchronized flow to free flow in the downstream direction, i.e., a gradual increase in the average speed of vehicles and correspondingly a decrease in the density of synchronized flow from detectors D2 to the detectors D4 [Fig. 3(b)]. One of the results of this obvious effect is that a gap between free flow and synchronized flow on the flux-density plane gradually disappears from the detectors D2 to D4, i.e., in the direction of traffic flow [Fig. 3(c)].

Phase transitions from free to synchronized flow are probably caused by the development of critical *localized perturbations of finite amplitude* which occur in free flow of higher density. To support this supposition, the dependencies of the speed and of the flux of the vehicles on the acceleration lane (the on-ramp) [Figs. 2(f)–2(h)]

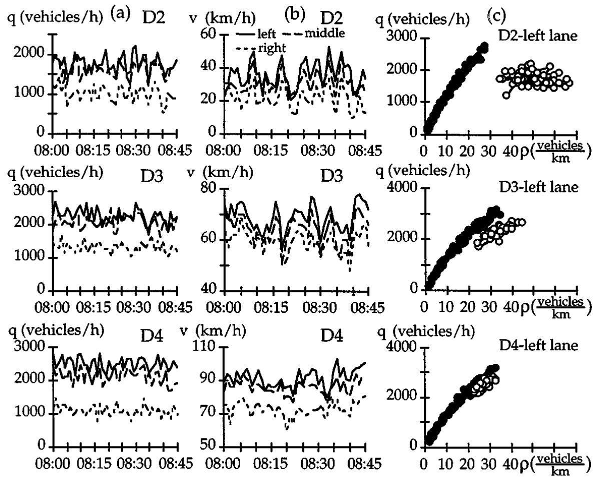

FIG. 3. The gradual spatial transition from synchronized to free flow in the downstream direction: (a), (b) the distributions of the flux (a) and of the average speed (b) for the different (left, middle, and right) lanes of the highway at the detectors D2, D3, and D4. (c) Free flow (black points) which is related to 5:30 $< t <$ 7:10 and synchronized flow (circles) which is related to (a), (b) on the flux-density plane. Circles on (c) for D4 left lane are related in more degree to a mixture of free and synchronized flow which is realized at $x = 2.2$ km.

have been examined. It turns out that on the one hand, the largest peak of the flux through the on-ramp appears at $t \approx$ 7:16 [Fig. 2(f)] and causes the peak in the flux of the vehicles at the detectors D3 [Fig. 2(e)]. On the other hand, at the same time $t \approx$ 7:16 the phase transition at the detector D3 occurs [Fig. 2(a)]. Therefore, it may be proposed that due to this peak of vehicles squeezing on to the highway a *deterministic* critical localized perturbation appears at $t \approx$ 7:16 [6]. The growth of this perturbation may cause the sharp decrease in the average speed of vehicles on the highway in the vicinity of the on-ramp. This local decrease in the average speed of vehicles should force the drivers squeezing on to the highway from the on-ramp to slow down too. The latter actually occurs after a certain time delay which is related to the upstream moving front of the wave of the induced transitions to the location of the detector D2 [Fig. 2(h)]. Note that as well as during the phase transition on the highway, the abrupt decrease in the speed of vehicles on the acceleration lane has almost no reaction in the flux of vehicles squeezing on to the highway [Fig. 2(f)]. The fairly high flux of *slow* moving vehicles squeezing on to the highway from the on-ramp, in turn, forces the drivers moving upstream from the on-ramp to slow down, too. This again leads to the maintenance of the low speed of the vehicles squeezing on to the highway, and so on. This may account for the continuation of synchronized flow long after the phase transition has occurred (about two hours) upstream from the detectors D3 [Fig. 1(b)].

Such effects of the self-maintenance of synchronized flow upstream from the on-ramp are observed as long as both the flux of vehicles squeezing on to the highway and the flux of vehicles on the highway upstream from the on-ramp are high enough. The backwards transition from synchronized to free flow at the detectors D1 occurs before (at $t =$ 9:29) the speed of vehicles at the on-ramp sharply increases (at $t =$ 9:35). It may thus be concluded that in the case under consideration this backwards transition is due to a decrease in the traffic volume coming upstream from the section of the highway. Note, that the empirical data show a *hysteresis effect* which accompanies the phase transition from free to synchronized flow. Indeed, both the flux of vehicles squeezing on to the highway and the flux on the highway upstream from the on-ramp which are necessary for the phase transition are considerably higher than they should be to allow a backwards transition from synchronized flow to free flow (more than about 50% for the first and 25% for the second flux, correspondingly). In other words, the phase transition from free to synchronized flow may be considered as a "first-order phase transition."

The empirical data show that phase transitions from free flow to synchronized flow can also occur on a highway section without on-ramps. In this case the whole localized region of synchronized flow as a rule moves upstream and is surrounded in upstream and downstream directions by free flow. This region is often a nonstationary one: Its width, its velocity, and the time-spatial distributions of the average speed, and of the flux of vehicles in synchronized flow inside this region can noticeably be changed in the course of time. After some time this moving localized region can either disappear or transform into a jam.

It should be emphasized that for basically similar initial states of free flow, where the fluxes of vehicles are in average nearly the same, there may be a random occurrence of phase transitions either to synchronized flow or to jams. It seems that the resulting kind of traffic (either synchronized flow or jams) depends on small peculiarities of the initial state of free flow. In the example shown in Fig. 4 a broad localized perturbation appears in a vicinity of the detectors D9 and D10 (7:16 $< t <$ 7:36, Fig. 4). The further development of this perturbation shows the self-formation process of a jam (D6, Fig. 4). In contrast to the phase transition from free to synchronized flow (Fig. 2), locally both the average speed and the flux of the vehicles decrease sharply during a jam's formation until both the speed and the flux reach zero even it if is only for a short time (Fig. 4). It should be noted that as long as free traffic is formed in the outflow from the jam, the phase diagram representing experimental data for free flow and the downstream front of a wide jam in the flux-density plane is basically the same here as in [5] [see Fig. 4(b) in [5]]. Therefore experimental data show that the phase transition from free flow to a traffic jam may be considered also (like the phase transition from free to synchronized flow) as a first-order phase transition occurring in a local region of the road (Fig. 4).

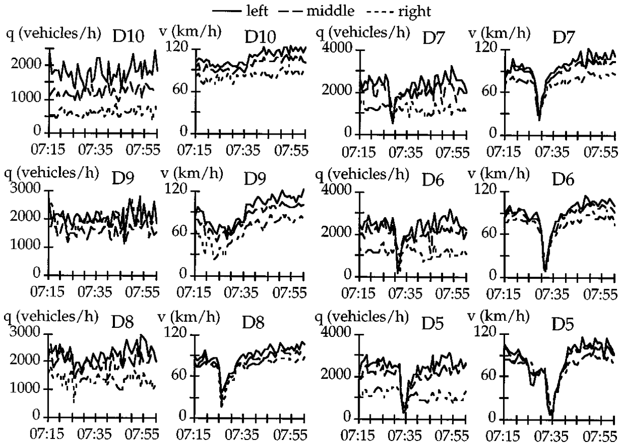

FIG. 4. The phase transition from free flow to the jam: the distribution of the flux and of the average speed of vehicles for the different lanes of the highway at the detectors D5–D10 in the time interval when the phase transition occurs.

The experimental data allow us to conclude the following:

(i) There are two different types of phase transitions from in average basically similar initial states of free flow: (a) either to synchronized flow or (b) to jams. Each of these phase transitions may be considered as first-order phase transitions. Because of the growth of either a deterministic localized perturbation or a random perturbation one of these two types of phase transitions occurs in a localized region of the highway. The deterministic perturbation is caused, for example, by a deterministic peak in the flux of vehicles squeezing on to the highway from an on-ramp. The random localized perturbation whose growth leads to phase transitions can also be realized on a highway section without on-ramps or bottlenecks.

(ii) A phase transition from free flow to synchronized flow caused by a peak in the flux of vehicles squeezing on to a highway from an on-ramp causes two deterministic processes: (a) a wave of induced transitions from free flow to synchronized flow in the upstream direction, and (b) a gradual spatial transition from synchronized flow to free flow in the downstream direction. After the phase transition has occurred the synchronized flow on the highway can further be *self-maintained for several hours.* This holds true even if the flux of vehicles squeezing on to a highway and the flux of vehicles on the highway upstream from the on-ramp become noticeably lower than the respective variables before the phase transition.

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