Experimental properties of complexity in traffic flow

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Experimental investigations of a complexity in traffic flow are presented. It is shown that this complexity is linked to space-time transitions between three qualitative different kinds of traffic: ''free'' traffic flow, ''synchronized'' traffic flow, and traffic jams. Peculiarities of ''synchronized'' traffic flow and jams that are responsible for a complex behavior of traffic are found. [S1063-651X(96)51805-2]

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I. INTRODUCTION

A spontaneous occurrence of complex space-time structures is a usual property of a lot of different nonequilibrium physical systems (e.g., [1]). As it follows from experimental investigations, an appearance of these structures is often accompanied by a very complex dynamical behavior of variables of the physical systems. Also in traffic flow, a very complex dynamical behavior of the variables of traffic has been found experimentally at a relatively high density of vehicles. In particular, on the flux-density plane such patterns represented an extremely broad scattering of the measurement points (e.g., [2,3]). In this Rapid Communication based on measured parameters of traffic that have been investigated on German highways, properties of the macroscopic structure of a complexity in traffic flow will be found.

II. MACROSCOPIC STRUCTURE OF COMPLEXITY IN TRAFFIC FLOW

Traffic flow on the German highways A3, A5, and A44 has been investigated on different days in 1991–1995. The properties and the macroscopic structure of complexity in traffic flow are found to be qualitatively similar for all cases. Therefore, we restrict our consideration here to only one case of traffic which occurred on Friday, August 25, 1995 on a section of the highway A5 between Bad Homburg and Frankfurt [Fig. 1(a)]. It allows one to show common results that have been found in different cases. The section of the highway A5 has already been discussed in [4]. It has three intersections (I1, ''Westkreuz Frankfurt''; I2, ''Nordwestkreuz Frankfurt''; and I3, ''Bad Homburger Kreuz'') with other highways, correspondingly. There are 16 sets of induction loop detectors (D1,...,D16) in this section. The sets of detectors D1, D4, D5, D7–D14, and D16 are situated on the road [Fig. 1(a)]. The other sets of detectors are situated inside the intersections. The road consists of a three-lane road, except for a short part (0.4 km) of the highway left of the intersection I1, where the highway has five lanes. Each set of the detectors D3–D16 consists of three detectors for a left (passing) lane, a middle lane, and a right lane, correspondingly. An induction loop detector produces two 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 the one minute interval.

Usual dependencies of the flux and of the average speed of vehicles in times showed complex time patterns [Fig. 1(b), left]. As it has been found earlier from a lot of measurements of traffic on highways in different countries (e.g., [2,3]), these time patterns represent on the flux-density plane a complex picture. In this picture two different regions of lower and higher density, where correspondingly ''free'' flow and ''congested'' traffic flow are realized, could be chosen [2,3] [Fig. 1(b), right]. One can see that as usual [2,3], congested traffic flow corresponded to an extremely broad scattering of the measurement points on the flux-density plane. When complex time patterns for different sets of detectors, which are situated on different locations, are compared, one can find that in reality these patterns correspond to the local measurements of the parameters of traffic flow in very complex space-time nonstationary structures in traffic.

To understand experimental properties of this complexity in traffic flow we will investigate congested traffic flow in more detail. We will restrict the consideration of traffic outside intersections, on- and off-ramps, exactly, when both the number of lanes does not change and all lanes on the highway correspond to the same route. We will find that even if no traffic jams in congested flow are taken into account, the rest of congested traffic flow, nevertheless, shows a very

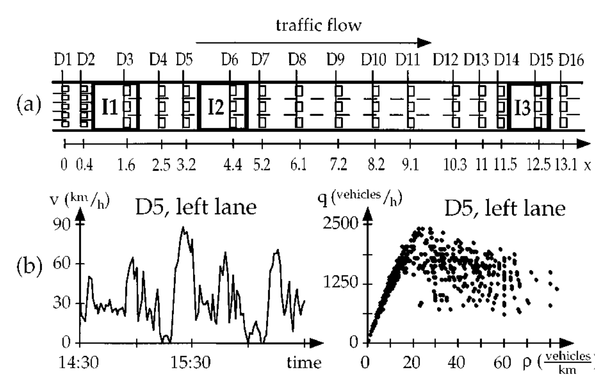

FIG. 1. Pattern in traffic flow: (a) Schematic configuration of the chosen section of the highway A5; (b) A fragment of a time pattern of the average speed of vehicles (left) and the measurement points on the flux-density plane (during the time 7:00–22:00) (right) at the detector D5 (left lane). (b) represents patterns in traffic that are qualitatively the same as those that have been observed earlier on highways in different countries (e.g., [2,3]).

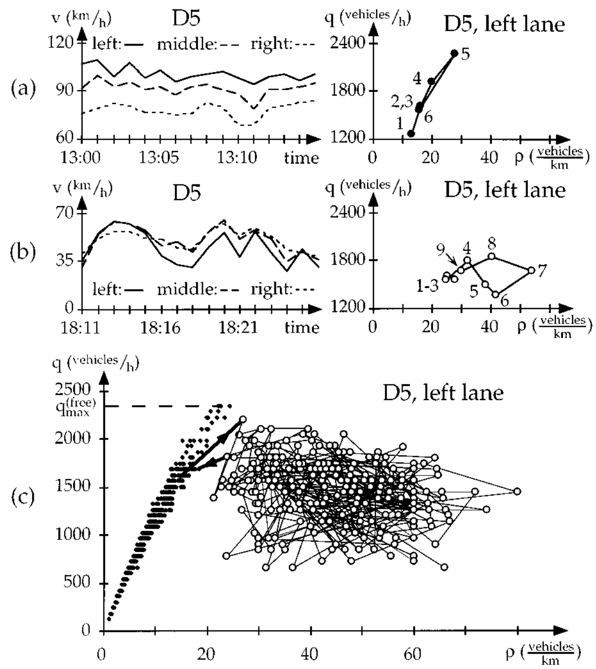

FIG. 2. Free traffic flow (a) and synchronized traffic flow (b): Fragments of the average speed of vehicles for the left, the middle, and the right lanes (left) and transferences between experimental points on the flux-density plane (solid lines) for the left lane (right). Experimental points 1–6 in (a) (right) correspond to the time 13:08–13:13; points 1–9 in (b) (right), 18:12–18:20. In Fig. (c) both experimental points corresponding to free traffic flow (black points) and to synchronized traffic flow (circles; the solid lines show transferences between experimental points) are presented (during the time 7:00–22:00, except short time intervals, when traffic jams were realized at the detector D5).

complex behavior. This congested flow consists, as a rule, of nonperiodical spatial alternations between different states of ''synchronized'' traffic flow. The synchronized flow corresponds to vehicles moving nearly synchronized in different lanes of the highway. We will see that a whole macroscopic structure of complexity in traffic flow consists of spatial alternations of states of three qualitative different kinds of traffic: ''free'' traffic flow, ''synchronized'' traffic flow, and traffic jams.

The average speed of vehicles in free traffic flow, where vehicles are able to change a lane and to pass, was essentially different in different lanes of the highways [Fig. 2(a), left]. In particular, it can be linked to the fact that the percentage of long vehicles was negligible in the left lane and it was relatively high (25%–50%) in the right lane of the highway. In free traffic an increase in the flux was accompanied, as a rule (in more than 90% cases), by the increase of the density [Fig. 2(a), right] and by the corresponding decrease in the average speed of vehicles. In other words, free traffic showed the well-known behavior on the flux-density plane (e.g., [2,3,5]) [Fig. 2(a), right]. Notice that free traffic flow, as it follows from Fig. 2(c), cuts off at some point $q_{\max}^{(\mathrm{free})}$.

It is known that the average speeds of vehicles in traffic flow can be nearly synchronized in different lanes of the highway (e.g., [2]). We will first consider properties of synchronized traffic flow without taking into account traffic jams, which are usually realized in congested flow. Experimental investigations show that in synchronized traffic flow vehicles could move with nearly the same average speeds in different lanes [Fig. 2(b), left]. In synchronized traffic the average speed of vehicles was noticeably lower [Fig. 2(b), left] and the density of vehicles was noticeably higher [Fig. 2(b), right] than the corresponding values in free traffic at the same flux of vehicles [Fig. 2(a)]. It can be assumed that in synchronized flow vehicles are almost not able to pass.

It has been found that contrary to free traffic, in synchronized traffic an increase in the flux could be accompanied both by an increase and by an decrease in the density [Fig. 2(b), right]. Correspondingly, the average speed of vehicles could both decrease and increase, when the flux increased. In other words, the measurements points performed random transferences in all directions both with positive and with negative slope on the flux-density plane. For this reason, these transferences of the measurement points for synchronized flow cover a two-dimensional region on the flux-density plane [Fig. 2(b), right]. The latter circumstance can distinctly be seen in Fig. 2(c), where both free [black points in Fig. 2(c)] and synchronized [circles in Fig. 2(c)] traffic flow for a longer time interval are presented. With the help of two arrows two transitions from free to synchronized traffic flow (at t=13:16) and backwards from synchronized to free traffic flow (at t=18:36) are also shown there.

As it has been stressed above, synchronized traffic flow showed the very complex dynamical behavior even without taking jams into account [Figs. 2(b) and 2(c)]. Nevertheless, some structures in this flow can be distinguished. There were three different types of states of synchronized traffic flow:

(i) Nearly both stationary and homogeneous states, when both the average speed and the flux were stationary during a relative long time interval (2–5 min) [see, for example, points 1–3 in Fig. 2(b), right].

(ii) States, where the average speed was nearly a stationary one during a relatively long time interval, but the flux, i.e., the density, noticeably changed during this time interval. It may be assumed that waves of the flux (and of the density) propagated with positive velocities in such synchronized traffic flow. Often the values of the flux did not change synchronized in different lanes of the highway. It can be assumed additionally that different waves of the density propagated in different lanes.

(iii) Essentially nonstationary and nonhomogeneous states, when both the average speed and the flux abruptly changed from one experiment point to the next one. It may be assumed that waves both with negative and with positive velocities may propagate in such synchronized traffic flow. Each of these three types of states of synchronized traffic flow covered on the flux-density plane two-dimensional regions.

Up to now we have premeditated not to take into account time intervals on Friday, August 25, 1995 when 10 different traffic jams occurred on the highway A5. The experimental investigations made show that—with regard to the occurrence of jams—in addition to the properties of complexity in traffic flow discussed above, the following ''elementary'' nonstationary space-time processes were important: (i) A random emergent of a nonstationary jam. (ii) A nonstationary growth of the amplitude and/or of the width of jams. (iii) An extinction of a jam. (iv) A merger of a few jams into one

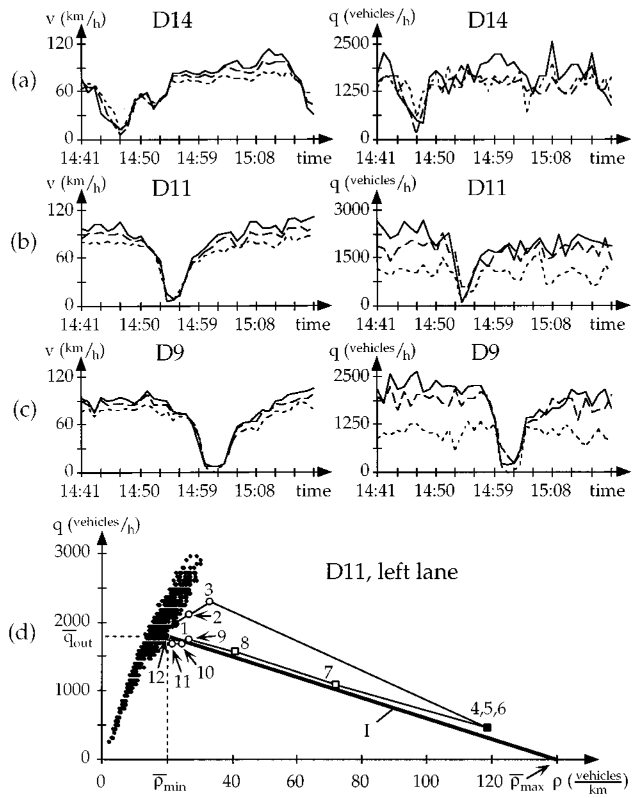

FIG. 3. Peculiarities of nonstationary traffic jams. (a)–(c) The kinetics of the traffic jam development: the dependencies of the average speed (left) and of the flux (right) on time for all three lanes [the designations of the lanes are the same as in Fig. 2(a)] at different detectors D14 (a), D11 (b), and D9 (c). (d) The representation of jams on the flux-density plane (the detector D11, left lane): thin solid lines show the transference between experimental points 1 and 4 (14:50–14:53) and 6 and 12 (14:55–15:01); the thick solid line I represents the downstream front of wide jams for the cases when no hindrance exists in the outflow from the jam [4]. $\overline{q}_{\rm out}\approx 1800$ vehicles/h, $\overline{\rho}_{\rm min}\approx 20$ vehicles/km and $\overline{\rho}_{\rm max}\approx 140$ vehicles/km are in agreement with those values which have been found in [4] for the left lane. Recall that $\overline{q}_{\rm out}$, $\overline{\rho}_{\rm min}$, and $\overline{\rho}_{\rm max}$ are the average flux out from the wide jam, the average density in the outflow from the jam, and the average density inside the jam, correspondingly. In (d) the points 4–6 that correspond to the measurements inside the jam are represented by one average point (black square).

jam. (v) An appearance of nonstationary moving blanks inside wide jams. The moving blanks which correspond, as a rule, to nonsynchronized flow of very high density have already been discussed in [4]. Notice that the recent theoretical analysis of a macroscopic traffic flow model has predicted a possibility of a self-formation of complex nonstationary jams in traffic flow [6]. The conclusions made in [6] have also been confirmed by the theoretical investigations of microscopic traffic flow models [7].

To show experimental characteristic properties of complexity in traffic flow that are linked to the occurrence in jams, we restrict our consideration to the processes (ii). A usual example of these processes is presented in Figs. 3(a)–3(c). The jam was first registered at $x=11.5$ km (the set of detectors D14), where it was a narrow one. It can be assumed that it occurred inside the intersection I3 [Fig. 1(a)]. During an upstream moving of this jam both its amplitude and its width grew in the course of time [Figs. 3(a)–3(c)]. It is linked to the experimental fact that in this case the average flux into the jam exceeded the average flux out from the jam. The latter circumstance becomes apparent in Fig. 3(d), where the upstream front and the downstream front of the jam are represented by the line between the points 3 and 4 and by the lines between the points 6, 7, and 8, correspondingly. One can distinguish the following important elements in the structure of complexity in traffic flow connecting to the occurrence of the jam:

(i) When the jam became a wide on (D9), the average velocity of its downstream front became nearly the same (≈ -15 km/h) as it followed from the slope of the average line for the jam's downstream front [the line I in Fig. 3(d)]. For example, the measured downstream front of the jam which was an almost wide one [Fig. 3(d), the lines between points 6, 7, and 8] was also found to be closer to this characteristic line found in [4].

(ii) The fronts of the jam, where the flux and the average speed abruptly changed [the lines between points 3 and 4 and 6, 7, and 8 in Fig. 3(d)] corresponded to nearly synchronized traffic. However, in this case they were essentially nonstationary and nonhomogeneous states of synchronized traffic flow.

(iii) Experimental investigations show that jams could be surrounded both by free and by synchronized traffic flow. Sometimes only upstream or only downstream of the jam free (or synchronized) traffic flow were realized. However, in cases where free traffic flow was realized upstream and downstream far from the jam, this free flow was nevertheless often separated upstream and/or downstream from the fronts of the jam by relatively short regions of synchronized traffic flow. The latter case is shown in Fig. 3(d), where the transitions from free traffic to synchronized traffic flow upstream of the jam (points 1 through 2) and from synchronized traffic to free traffic (points 9 through 12) were realized. Besides, experimental data show that if distances between two or more moving jams were small (about 1.5 km or less), as a rule, synchronized flow was realized between these jams.

To find a macroscopic structure in the complexity in traffic flow we have already distinguished in the congested region between synchronized flow shown in Figs. 2(b) and 2(c) and traffic jams (Fig. 3). Properties of these two kinds of traffic have been found above to be qualitatively different: A development of any jam whose width monotonically increased in the course in time showed a tendency to the *self-organization* of the downstream front of the jam to the average line for the jam's downstream front [the line I in Fig. 3(d)]. This means that the experimental points corresponding to the downstream front of the jams became close to this characteristic line when the jam became a wide one. In contrast, synchronized flow [Figs. 2(b) and 2(c)] did not show this kind of tendency but performed random transferences of the measurement points in all directions on the flux-density plane. Notice that to describe these qualitatively different properties of both jams and of synchronized flow, the whole congested region may not be substituted on the flux-density plane by one average curve. Indeed, already one average line [the line I in Fig. 3(d)] would be necessary only for the description of the properties of the downstream front of a wide jam.

III. CONCLUSIONS

The experimental data showed the following. (i) A picture of the complexity in traffic has a macroscopic structure that is linked to space-time transitions between states of three qualitative different kinds of traffic: free traffic flow, synchronized traffic flow, and traffic jams. (ii) Even if in congested traffic flow no traffic jams are taken into account, the rest of the congested traffic flow shows a very complex behavior. In particular, this part of the congested traffic flow consists of spatial alternations between different both with stationary and nonstationary states of synchronized traffic flow. The latter flow corresponds to vehicles moving with nearly synchronized average speeds in different lanes of the highway. The measurement points corresponding to the states of synchronized traffic flow perform random transferences in all directions both with positive and with negative slope on the flux-density plane. Spatial alternations of different states of free and of synchronized traffic flow can already lead to very complex structures in traffic flow. (iii) An occurrence of different jams makes a picture of the complexity in traffic flow more diverse. Traffic jams can be surrounded both by free and by synchronized traffic flow. A development of different nonstationary jams in which widths monotonically increase in the course of time shows the tendency to the self-organization of the downstream front of these jams.

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