# Experimental Features of Self-Organization in Traffic Flow

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Features of the "stop-and-go" phenomenon are found. First, the local phase transition "free flow $\rightarrow$ synchronized flow" is realized. Then the "pinch effect" in synchronized flow occurs. In the pinch region a complex sequence of narrow jams is self-formed. The following transformation of the narrow jams into wide jams determines a scale in distances between stop-and-go patterns. [S0031-9007(98)07447-X]

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Almost every driver met the "stop-and-go" phenomenon, i.e., a complex flow pattern consisting of numerous traffic jams (e.g., [1]). Already in 1958 Chandler, Herman, Montroll, Komentani, Sasaki [2], and later other authors (e.g., [3]) proposed that there is a density range where homogeneous states of traffic flow due either to an instability or to some other kind of phase transitions *cannot* exist and therefore the stop-and-go phenomenon has to occur [2,3]. A different scenario of self-organization has been proposed in 1994 by Kerner and Konhäuser [4], and later in other papers [5]: *Before* the mentioned density range is reached, there should be a broad range of lower densities where homogeneous states of free traffic flow are *metastable* states and "the local cluster effect" leading to jam formation can occur. While experimental features of jam's propagation in free traffic flow [6] are in good agreement with the theory of the local cluster effect [4], experimental data suggest that homogeneous states of traffic flow *can* exist in the whole possible vehicle density range [7,8]. Apparently for this reason, it turns out that *the real* scenario of self-formation of stop-and-go patterns found out in the Letter shows peculiarities which have not yet been found in traffic flow theories (see [1–5] and references there).

Between 1995 and 1998 stop-and-go traffic flow on the German highways A5, A1, A44, and A3 have been investigated on different days. It has been found out that the features of this phenomenon are similar in all cases. Therefore, general results made in the article may be illustrated by *representative* data sets measured on a section of the highway A5 [Figs. 1, 2(a), 2(b), and 3]. The section of the highway has three intersections with other highways (I1, "Friedberg," I2, "Bad Homburger Kreuz," and I3, "Nordwestkreuz Frankfurt") and is equipped with 24 sets of induction loop detectors $(D1, \ldots, D24)$ [Fig. 1(a)]. Each of the sets D4-D6, D12-D15, and D23, D24 consists of four detectors for a left (passing), a middle, and a right lane, plus one for the lane related to on-ramps or to off-ramps. The other sets of detectors are situated on the three-lane road without on- and off-ramps, where each of them thus consists of three detectors only. Each induction loop detector records the crossing of a vehicle and measures its crossing speed. A local road computer calculates the flow rate and the average vehicle speed in 1 min intervals.

Numerous observations suggest that, if an initial state of traffic flow is free flow, only *single* jams can be self-formed (an example is shown in Fig. 4 in [8]). In contrast, stop-and-go traffic flow has been observed, if an initial state of traffic flow is synchronized flow. The general features of the stop-and-go phenomenon are as follows:

(i) A local phase transition from free to synchronized flow occurs [Fig. 1(b), D6, up arrow at 6:27] [9]. This synchronized flow persists over a long time.

(ii) Numerous *narrow* jams, which move and grow in the upstream direction, appear [down arrows 1–8; D4, Fig. 1(b)] [10]. The velocity of narrow jams $v_{g,\mathrm{narrow}}$ is more negative than the velocity of the downstream front of wide jams $v_g$: $v_{g,\mathrm{narrow}} \approx (1.1–1.3)v_g$.

(iii) If the distance between growing narrow jams is relatively low, then after the growth of one of the narrow jams has finished by a formation of the first wide jam [solid down arrows 1; D4-D1, Fig. 1(b)], either (1) those narrow jams which are nearest to the wide jam in the downstream direction catch up and merge with it and/or (2) the further growth of nearest narrow jams is damped [Fig. 1(b), dotted down arrows 2, 3; D4-D2]. Only the growing of a narrow jam which is far enough downstream of the wide jam leads to the formation of a second wide jam [solid down arrows 4, D4-D1, Fig. 1(b)]. After the second wide jam has been formed, the process either of the damping or of the merger of the narrow jams which are nearest to this wide jam in the downstream direction is repeated, and so on [dotted down arrows 5 or 7; D4-D2, Fig. 1(b)]. As a result, a sequence of wide jams is self-formed. There is a certain scale [2.5–5 km, Fig. 1(b)] in distances between the downstream fronts of these wide jams [solid down arrows 1, 4, 6, 8; D1, Fig. 1(b)]. This scale can be noticeably higher than the mean distance between narrow jams [down arrows 1–8; D4, Fig. 1(b)]. After the sequence of wide jams has been formed, no narrow jams occur between the wide jams anymore even if synchronized flow is formed in the outflow of a wide jam [D1, Fig. 1(b)].

  

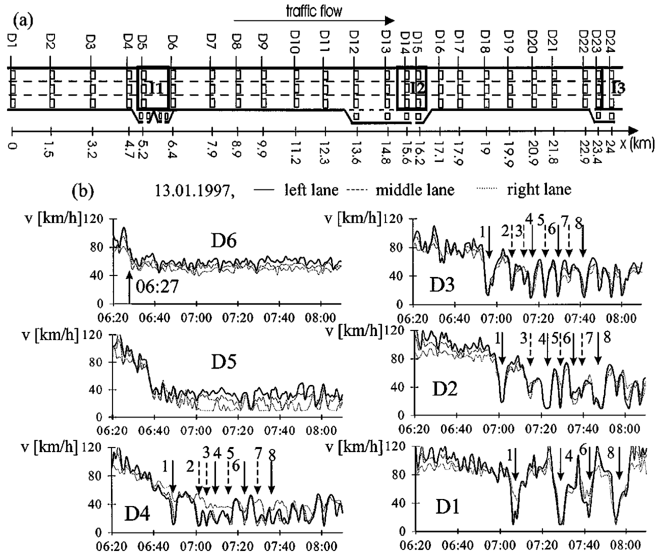


FIG. 1. Stop-and-go phenomenon: (a) Schematic configuration of the highway section. (b) The dependence of the vehicle speed at different detectors on time.

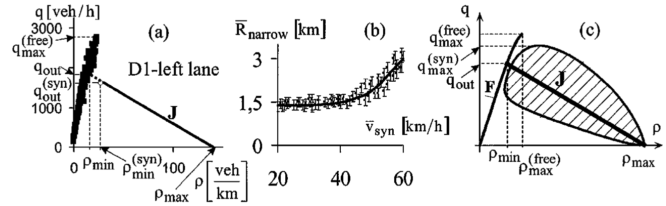


FIG. 2. Properties of the stop-and-go phenomenon: (a) The line $J$ for the wide jam in Fig. 1(b) related to the arrow 1, and the free flow (black points). $q_{out} \approx 1800$ vehicles/h, $q^{(syn)}_{out} \approx 1570$ vehicles/h, $\rho_{min} \approx 20$ vehicles/km, $\rho^{(syn)}_{min} \approx 28$ vehicles/km, $\rho_{max} \approx 140$ vehicles/km, and $v_g \approx -15$ km/h. (b) Dependence of the mean distance between centers of narrow jams on the average vehicle speed between jams in the pinch region (solid curve) which was derived by averaging 216 actual data points from 42 days during 1996–1998 on the highway A5 [Fig. 1(a)]. (c) A schematic concatenation of states of free flow (curve $F$) and of states of synchronized flow (hatched region) with the line $J$. The regions of homogeneous and nonhomogeneous states of synchronized flows are quantitatively approximately the same in the flow-density plane (hatched region); the left and the upper delimiting points of these regions approximately are (20 vehicles/km, 1600 vehicles/h) and (40 vehicles/km, $q^{(syn)}_{max} \approx 2600$ vehicles/h) (left lane). Note that the existence of three qualitatively different phases of traffic [7], (i) Free flow, (ii) synchronized flow, and (iii) jams, indicates that highway capacity depends on which phase (i, ii, or iii) the traffic is in. The related "maximal capacity" for free flow is $q^{(free)}_{max}$, for synchronized flow it is $q^{(syn)}_{max}$, and downstream of a wide jam it is $q_{out}$. $q^{(free)}_{max}/q_{out} \approx 1.5$ [6]. Usually $q^{(free)}_{max} \gtrsim q^{(syn)}_{max} > q_{out}$.

(iv) Independently on whether free or synchronized flow is formed in the outflow of wide jams their downstream fronts move stationary with the same mean velocity $v_g$. Therefore, as in [6], the downstream fronts of the jams may be represented in the flow-density plane by the characteristic line for the downstream front of a wide jam which as of now will be designated as *the line J* [Fig. 2(a)]. However, if synchronized flow is formed in the outflow of the jams as it occurs in Fig. 1(b) (D1), then the flow out of a jam $q^{(syn)}_{out}$ can be lower and the vehicle density in the outflow of the jam $\rho^{(syn)}_{min}$ can be higher than the related average values $q_{out}$ and $\rho_{min}$ for the case considered in [6] when free flow was formed in the outflow of wide jams. Besides, $q^{(syn)}_{out}$ and $\rho^{(syn)}_{min}$ are noticeably changing over time. Therefore, the left coordinate of the line $J$ which is approximately related to the point $(\rho^{(syn)}_{min}, q^{(syn)}_{out})$ [Fig. 2(a)] performs complex slides along the line $J$ over time.

(v) The processes of the spontaneous appearance, the growing, and the upstream moving of narrow jams mentioned in item (ii) are realized in a region of a highway where states of synchronized flow outside of narrow jams are lying noticeably above the line $J$ in the flow-density plane. The latter effect is linked to a spatial compression of synchronized flow; the vehicle speed is lower and the density is higher in this region [e.g., in Fig. 1(b) outside of narrow jams the mean vehicle speed and the density were as follows: at D6, $\overline{v}_{syn} \approx 60$ km/h, $\overline{\rho}_{syn} \approx 28$ vehicles/km; at D5, $\overline{v}_{syn} \approx 35$ km/h, $\overline{\rho}_{syn} \approx 45$ vehicles/km; at D4, $\overline{v}_{syn} \approx 40$ km/h, $\overline{\rho}_{syn} \approx 40$ vehicles/km; at D3, $\overline{v}_{syn} \approx 57$ km/h, $\overline{\rho}_{syn} \approx 28$ vehicles/km]. The compression of synchronized flow, where (1) states of flow are lying noticeably above the line $J$ in the flow-density plane and (2) a sequence of growing narrow jams spontaneously occurs, can be called a *"pinch effect" in synchronized flow.* The related region of a highway where the pinch effect occurs can be called a *"pinch region."* The downstream boundary of the pinch region is usually situated in the vicinity of the location on a highway where synchronized flow is either maintained or self-maintained [Fig. 1(b), D6]. The upstream boundary of the pinch region is usually correlated with the location where narrow jams begin to transform into wide jams [D3 in Fig. 1(b)].

(vi) Inside the pinch region the mean distance between centers of narrow jams $\overline{R}_{narrow}$ is an increasing function of the vehicle speed in synchronized flow where the narrow jams emerge [Fig. 2(b)]. However, after narrow jams have transformed into wide jams, distances between them can retain over long time independently both on the speed of vehicles and on whether synchronized or free flow is formed between the wide jams.

Observations show that both synchronized flow and the pinch effect, which triggers off the self-formation of stop-and-go patterns, occur *considerably more frequently* in the vicinity of on-ramps, off-ramps, and other freeway bottlenecks. It is clear that a bottleneck introduces a permanent nonhomogeneity in traffic flow. It can be suggested that this nonhomogeneity plays the role of a "trigger" ("*permanent* nucleus") for the phase transition "free → synchronized flow" and for further either maintaining or self-maintaining of synchronized flow [8]. However, self-organization can occur in traffic flow outside any bottlenecks. An example of this is shown in Fig. 3. Here the whole chain of processes: (1) The phase transition free → synchronized flow (at $t \approx 06{:}36$, D18, up arrow), (2) the following induced transitions upstream (D17, up arrow) and propagating synchronized flow downstream (D19, D20, up arrows), (3) the pinch effect (D20), (4) self-formations of a narrow jam (at $t \approx 06{:}50$, D20, down arrow) which (5) then becomes a wide jam (D17, down arrow) occur *outside* on- and off-ramps. A single jam (down arrows) is self-formed in synchronized flow because the synchronized flow in this case is self-maintained only during a relatively short time interval. Observations suggest that the formation of single jams in an initial free flow owing to such "double" phase transitions "free → synchronized flow → jam" (Fig. 3) is a considerably more frequent event that the "direct" phase transition "free flow → jam".

It may be concluded that the following main processes accompany the self-formation of stop-and-go patterns: (i) occurrence of a phase transition free → synchronized flow, (ii) maintaining of synchronized flow for a long time, (iii) occurrence of the pinch effect in synchronized flow where growing narrow jams appear propagating upstream. The mean distance between centers of emerging narrow jams $\overline{R}_{\text{narrow}}$ is an increasing function of the vehicle speed in the pinch region. (iv) When $\overline{R}_{\text{narrow}}$ is relatively low, then after the growth of one of the narrow jams has finished by the self-formation of a wide jam, either narrow jams nearest to this wide jam are suppressed and/or they merge with the wide jam. Only a narrow jam which is far enough from the wide jam in the downstream direction leads to the formation of the next wide jam. This successive process of self-organization determines a scale in distances between the wide jams. (v) Independently on the state of flow which is formed in the outflow of wide jams, their downstream fronts propagate stationary with the same mean velocity.

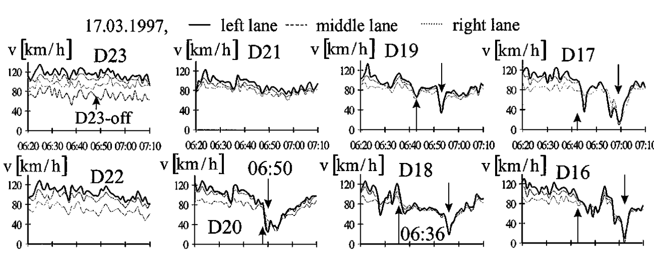


FIG. 3. Self-organization without bottlenecks: Dependencies of the vehicle speed on time at the detectors D23-D16 shown in Fig. 1(a).

To explain the conclusions (i)–(iv), recall that (1) homogeneous states of synchronized flow cover a *two-dimensional* region in the flow-density plane [hatched region in Fig. 2(c)] [7,11] and (2) metastable states of free flow are related to the density range $\rho_{\min} \le \rho \le \rho_{\max}^{(\text{free})}$ [Fig. 2(c)] [4,6]. In Fig. 2(c) it has also been taken into account that homogeneous states of synchronized flow and states of free flow overlap in densities [see Fig. 3(c), D3 in [8]]. Considering states of both free and synchronized flow, note that wide jams *cannot* be formed in any states of flow situated *below* the line $J$ [Fig. 2(c)]. Indeed, let a state of flow directly upstream of a wide jam be related to a point "$b$" in the flow-density plane which is below the line $J$. Because the value of the velocity of the upstream front of a wide jam $v_g^{(\text{upstream})}$ equals the slope of a line from $b$ to the point $(\rho_{\max}, 0)$, the related absolute value $|v_g^{(\text{upstream})}|$ is always lower than that of the downstream front $|v_g|$ given by the slope of the line $J$. Therefore, the width of the jam is gradually decreasing. Otherwise, if a flow which is upstream from a wide jam is *above* the line $J$, then $|v_g^{(\text{upstream})}| > |v_g|$; i.e., the width of the jam is gradually increasing. Therefore, wide jams can be formed in states of flow above the line $J$. On the other hand, observations suggest that states of both free and synchronized flow above the line $J$ *can exist* for a long time [7,8]. Therefore, it may be proposed that (i) the line $J$ determines *the threshold* of the jam's existence and (ii) the line $J$ separates all homogeneous states of both free and synchronized flow into two qualitatively different classes: (1) In states which are related to points in the flow-density plane lying below the line $J$ no jams can be excited or exist, and (2) states which are related to points in the flow-density plane lying on and above the line $J$ are "*metastable*" states. In the metastable states *only* those local fluctuations whose amplitude exceeds some *critical amplitude* grow and can lead to a jam formation. Although it is not possible to give quantitative results about the critical density fluctuations [12], some qualitative conclusions may be suggested [13]. Note that the critical amplitude is maximal (it is a finite value because it cannot exceed the jam density) on the line $J$ [Fig. 2(a)]; i.e., the probability of the growth of local perturbations in the related states of flow is extremely small. Because a synchronized flow *directly* downstream of a wide jam is related to a point $(\rho_{\min}^{(\text{syn})}, q_{\text{out}}^{(\text{syn})})$ being in the vicinity of the line $J$ [Fig. 2(a)], the growth of narrow jams nearest to the wide jam downstream is suppressed. However, even if the flow rate downstream remains the same, states of flow which are *far enough* downstream of the jam, in the pinch region, lie noticeably above the line $J$, because (1) states of synchronized flow cover a *two-dimensional* region in the flow-density plane [Fig. 2(c)] and (2) the vehicle density in the pinch region is considerably higher than $\rho_{\min}^{(\text{syn})}$ [Fig. 2(a)]. As a result, the critical amplitude of local fluctuations in these states may be considerably lower than on the threshold, the line $J$. For this reason, local fluctuations may grow in the pinch region. This may explain the occurrence and the spatial scale of stop-and-go patterns. In contrast, if free flow is formed on the outflow of a wide jam, the state of this free flow is always related to the point $(\rho_{\min}, q_{\text{out}})$ lying on the line $J$ [Fig. 2(a)]. Therefore, the probability of new jams downstream is extremely small, and only *single* jams could be observed in free flows.

To explain the conclusion (v), note that the moving of the downstream front of a wide jam is a deterministic process of drivers' escaping from the jam. The velocity $v_g$ of this process is determined by the density $\rho_{\max}$ and by an average delay time $\tau_{\text{del}}$ between two vehicles following one another escaping from the jam:

$$v_g = -1/(\rho_{\max}\tau_{\text{del}}). \quad (1)$$

Indeed, on the one hand, each driver standing inside the jam can start to escape from the jam after (i) the vehicle in front of him has already escaped the jam and (ii) the distance between these drivers has exceeded some "safety distance" $d_{\text{del}}$. Therefore, there is the corresponding time delay $\tau_{\text{del}}$ [$\tau_{\text{del}} \approx 1.7$ s for the parameters of the line $J$ in Fig. 2(a)] [14]. On the other hand, the average distance between vehicles which stand inside the jam, including an average length of vehicles, equals $1/\rho_{\max}$. The parameters $\rho_{\max}$ and $\tau_{\text{del}}$ do not depend on the state of flow in the outflow from the jam. Therefore, the velocity $v_g$ (1) does not depend on the state of flow which is formed in the outflow of the jam either.

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[9] Features of this phase transition have been considered in [8].

[10] Note that a *narrow* jam is a jam which consists of only upstream and downstream jams' fronts; vehicles do not come in average to a stop inside a narrow jam. On the contrary, the width of a *wide* jam is noticeably higher than the widths of jams' fronts [6,7].

[11] B. S. Kerner, in *Proceedings of the Third International Symposium on Highway Capacity*, edited by R. Rysgaard (Road Directorate, Denmark, 1998), Vol. 2, p. 621.

[12] Indeed, (1) critical fluctuations in the pinch region are highly growing between detectors [Fig. 1(a)] without possibility to be measured and (2) the spatial scale making out in measured data is only $\approx 0.26-0.32$ km (the mean velocity of fluctuations is $\approx -16--19$ km/h and the time scale of data is 1 min).

[13] Note that two results of the observations: (1) the shape of the function in Fig. 2(b) and (2) that the double phase transitions free $\rightarrow$ synchronized flow $\rightarrow$ jam (Fig. 3) are considerably more frequent than the phase transition free flow $\rightarrow$ jam allow to suggest that the lower the vehicle speed is the lower the critical amplitude of fluctuations for states of flow being at the same distance from the line $J$ in the flow-density plane.

[14] Note that $\tau_{\text{del}}$ determines the flow rate $q_{\text{out}}$: $q_{\text{out}} = (1/\tau_{\text{del}})[1 - (\rho_{\min}/\rho_{\max})]$. This formula follows from (1) and $v_g = -q_{\text{out}}/(\rho_{\max} - \rho_{\min})$. [B. S. Kerner, in *Transportation Systems*, edited by M. Papageorgiou and A. Pouliezos, Preprints (Technical University of Crete, Chania, Greece, 1997), Vol. 2, p. 793.]