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**LETTER TO THE EDITOR**

# Experimental features of the emergence of moving jams in free traffic flow

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**Abstract.** Conditions and features of jam emergence in free traffic flow are found. Observations show that a 'free flow → jam' phase transition can occur *only if* the formation of synchronized flow is strongly hindered due to *a non-homogeneity*, in particular at a traffic split on a highway.

Empirical and theoretical investigations of nonlinear features of congested traffic flow have become an important subject of physical and mathematical research (see, e.g., reviews and references in [1–3]). To distinguish between free and congested states, experimental points measured at a fixed location on a highway are often studied in the flow–density plane (e.g., [4]). When traffic flow is a free flow then experimental points nearly lie on a curve with a positive slope in the flow–density plane. This curve is cut off at a limit (maximum) point ($q_{\max}^{(\text{free})}$, $\rho_{\max}^{(\text{free})}$, see, e.g., figure 2(*d*) in [5]) in the flow–density plane. Congested states can be defined as the states of traffic where the average vehicle speed is lower than the minimum vehicle speed in free flow related to this limit point. In contrast to free flow, there is a tendency to a synchronization of the average vehicle speeds across different highway lanes in congested traffic. This leads to the synchronization of the average vehicle speeds away from on- and off-ramps and other bottlenecks, in particular in so-called 'stop-and-go' traffic [4].

Recently the author has discovered that two qualitatively different traffic phases must be distinguished in congested traffic: synchronized flow and wide moving jams [6–9]. Therefore, there are three traffic phases: (1) free flow, (2) synchronized flow and (3) wide moving jams. In particular, while states of free flow can really be represented by a curve in the flow–density plane, *even* the multitude of hypothetical homogeneous and stationary in time states of synchronized flow ('steady speed' states) cover a two-dimensional region in the flow–density plane: a given vehicle speed in a steady speed state of synchronized flow may be related to an infinite multitude of vehicle densities, and a given density may be related to an infinite multitude of different steady speeds.

All phase transitions between these traffic phases are local first-order transitions, i.e., they are accompanied by breakdown, hysteresis and nucleation effects [7]. A recent correlation analysis of traffic data [10] has confirmed features of the traffic phases (1)–(3) discovered in [6–8]. Note that traffic flow is a very complex nonlinear dynamics process, which occurs in both time and space. Therefore, to distinguish between traffic phases and to understand features of phase transitions in traffic flow a spatial–temporal behaviour of traffic has to be studied. For such an empirical study simultaneous measurements of traffic at different spatial

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locations on a highway have to be made. Related objective criteria to identify the traffic phases and phase transitions which are essentially linked to the simultaneous measurements of traffic at spatial different locations on a highway can be found in [5–9, 11–13].

It has recently been found [8] that both at on-ramps and away from bottlenecks moving jams emerge in free flow due to a sequence of two phase transitions: 'free flow → synchronized flow → jam(s)' (this sequence of phase transitions will be designated as the 'F → S →J transitions'; consequently, the phase transition from free flow to synchronized flow as the F→S transition and from synchronized flow to jam(s) as the S → J transition). It must be noted that the S → J transition in this sequence occurs *later* than the F → S transition. Besides, the location on the highway where the S → J transition occurs usually *differs* from the location of the first F → S transition [5, 8].

These experimental results are in some sense in contrast to the other experimental result that free flow is in a metastable state with respect to jam emergence at $q \geqslant q_{\mathrm{out}}$ (and respectively at $\rho \geqslant \rho_{\mathrm{min}}$, see figure 2(*d*) in [5]) [11]. Indeed, the latter result means that there should be some conditions for a 'free flow → jam(s)' phase transition (this will be designated the 'F → J transition'). Such conditions, however, have not been found in experiments up to now. Results of observations presented in this letter allow us to suggest that the F → J transition can occur *only if* the formation of synchronized flow is strongly hindered due to *a non-homogeneity* on a highway.

Between 1995 and 1999 jam emergence on German highways A1, A3, A5 and A44 has been studied. General results from this study may be illustrated by a representative data set (figures 1 and 2) measured on a section of the A5-south highway (figure 1(*a*)) on 23 June 1998. The section and the characteristics of the data have been considered in [8]. Different from figure 1(*a*) in [8], it has now symbolically been marked in figure 1(*a*) that a few hundred metres downstream of the detector D23-off, the off-ramp splits in two roads running into two directions (west and east) on the highway A66 which crosses the highway A5 at intersection I3. Therefore, there are two detectors: D24-off-1 for the east direction and D24-off-2 for the west direction (figure 1(*a*)). This circumstance has not been important for phase transitions at the on-ramps (D6 and D16, figure 1(*a*)) and away from bottlenecks studied in [5–9, 11–13]. However, it is important for a study of phenomena at off-ramps which will be presented below.

An overview of the representative data set is shown in figure 1(*b*). The following phenomena occurred on 23 June 1998. (i) A moving jam emerged in I3 at about 7 am (D23, figure 1(*a*)). (ii) The jam propagated further through the whole highway section [5]. (iii) Propagating in the vicinity of the on-ramp (D16, figure 1(*a*)), the jam caused the F → S transition at this on-ramp: the jam played the role of a nucleus for the F → S transition at the on-ramp [7, 13]. (iv) As a result of the F → S transition, a pinch region was formed in synchronized flow upstream of the on-ramp (the pinch region 1 in figure 1(*b*), left). The synchronized flow was self-maintained for a long time [8]. (v) Independent of phenomena (i)–(iv), another pinch region (the pinch region 2 in figure 1(*b*), left) was formed upstream of the off-ramp (D23-off). The consideration below will only be restricted to a study of phenomenon (i): the emergence of the moving jam at intersection I3.

First recall that the dependences of the vehicle speed and the flow rate on time, which are typical during the F → S transition, show the same peculiarities either away from bottlenecks or at on-ramps [8]. In these cases, it is the S → J transition which is responsible for the jam emergence (see figures 1 and 3 in [8]).

To answer the question of whether and when the direct emergence of a jam in free flow is possible, additional observations of more than 700 emergences of moving jam(s) on 183 days in 1995–99 have been studied. It turns out that at on-ramps and away from bottlenecks the F → J transition could *never* be observed: jam(s) emerge *only* due to the sequence of the

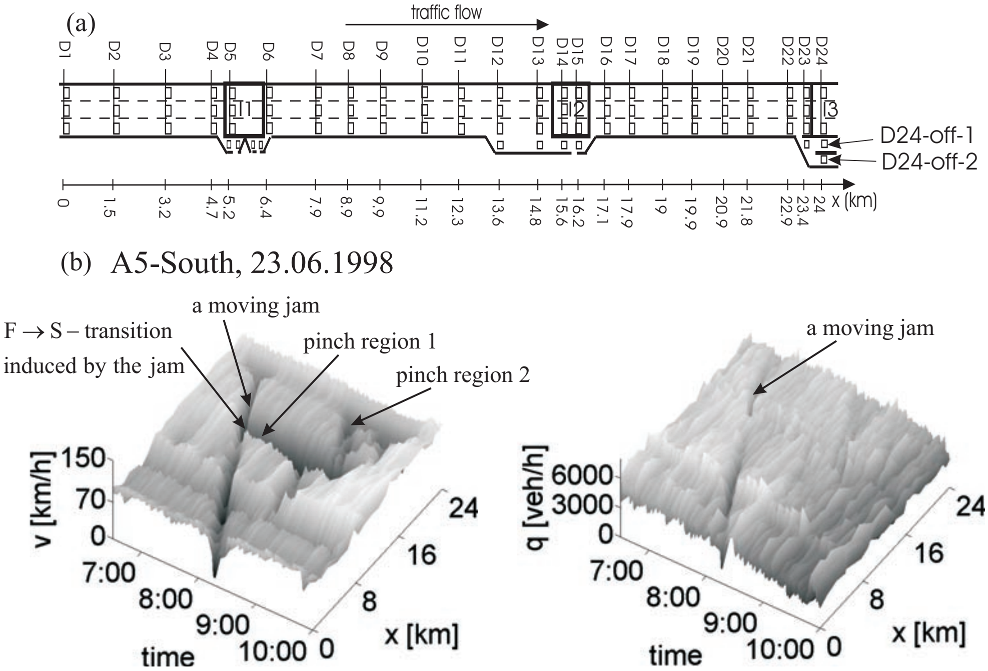


**Figure 1.** An overview of a traffic pattern on 23 June 1998: (*a*) the schematic configuration of the highway section; (*b*) dependences of the average (across all lanes) vehicle speed (left) and the total flow rate across the highway (right) on time and space.

F → S → J transitions. Therefore, the existence of the limit point of free flow ($q_{\max}^{(\text{free})}$, $\rho_{\max}^{(\text{free})}$) (see figure 2(*d*) in [5]) is linked in these cases to the F → S transition rather than to the F → J transition [5]. However, in the range of the flow rate $[q_{\text{out}}, q_{\max}^{(\text{free})}]$ (and the density $[\rho_{\min}, \rho_{\max}^{(\text{free})}]$) free flow *must* be metastable with respect to the jam emergence [11]. This contradiction of observations can be solved if it is suggested that at any density in free flow the critical amplitude of local perturbations of traffic variables (speed or/and density) in free flow needed for the F → S transition is considerably lower than that needed for the F → J transition. However from the data it is not possible to make a direct measurement of the related critical amplitudes [8]. Nevertheless, the problem can be solved in a different way.

It may be proposed that the synchronization of the speeds can be *hindered* at an off-ramp (or at all locations where traffic is splitting up into at least two routes). If the fraction of vehicles which have to choose the off-ramp is high enough, then these vehicles in the vicinity of the off-ramp *may not* change to those lanes which are related to the straight route even if the vehicle speed is higher there. Therefore the F → S transition should be hindered in this case.

In the latter case the mentioned vehicles remain on the lane(s) related to the off-ramp even if a local perturbation of large amplitude occurs at the off-ramp. Such a perturbation often occurs on working days at the off-ramp at intersection I3 (down arrow 1 in figure 2(*a*)). If this perturbation due to its propagation upstream finds itself in metastable states of free flow and if the amplitude of the perturbation is high enough, then it can be expected that the perturbation grows and leads to the F → J transition (figure 2(*b*), down arrows 1).

The features of this phenomenon are the following:

(i) In the vicinity of the off-ramp the flow rate on the right lane becomes approximately as high as on the left lane (figure 2(*b*), D22). A local perturbation occurs *only* on the right

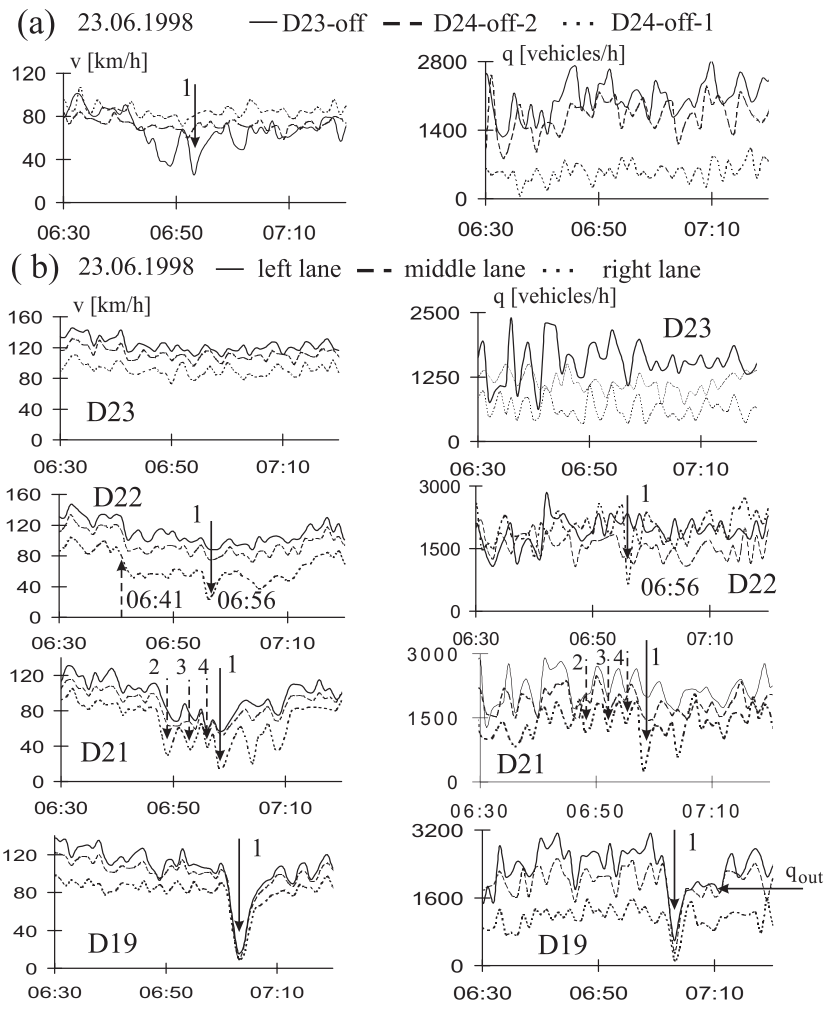


**Figure 2.** The F → J transition: (*a*), (*b*) dependences of the vehicle speed (left) and the flow rate (right) for each lane at different detectors in the vicinity of intersection I3 (figure 1(*a*)) on time. The horizontal arrow at D19 (right) shows the level of the flow rate out of the jam on the left lane, $q_{out}$.

lane (down arrow 1 at 06:56 in figure 2(*b*), D22). This perturbation does *not* cause the F → S transition, i.e., no synchronization of speeds between different lanes occurs. Note that, on the contrary, in locations away from bottlenecks or at on-ramps the flow rate on the right lane is noticeably lower than on the left lane. Also in those locations the F → S transition occurs instead of the F → J transition [7].

(ii) As can be seen in figure 2(*a*) (down arrow 1), the local perturbation mentioned in item (i) has initially emerged downstream of the detectors D22 inside the off-ramp. This perturbation is related to a sharp decrease in the vehicle speed but the flow rate remains high (D23-off, figure 2(*a*), right). The flow rates and the speeds at the downstream detectors D24-off-1 and D24-off-2 are not disturbed. Therefore the perturbation is not induced by traffic on the cross highway A66. Also the perturbation is not induced downstream of the highway (D23, figure 2(*b*)).

(iii) The growth of the initial local perturbation (down arrow 1, D23-off, figure 2(*a*)) leads to

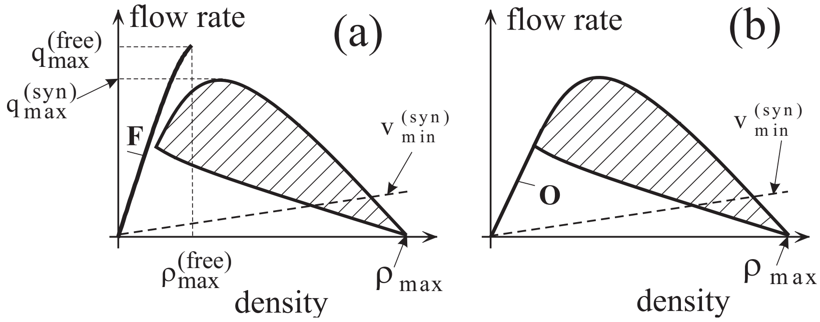


**Figure 3.** A hypothesis about homogeneous states of traffic flow [9]: (*a*) multitudes of homogeneous states of free (curve F) and of synchronized flow (hatched region) on a multi-lane road. (*b*) A multitude of homogeneous states of flow on a one-lane road.

the jam emergence in the free flow upstream (down arrow 1, D19, figure 2(*b*)). When the width of the jam becomes wide enough, the jam shows the features which are characteristic for wide jams [11]. In particular, the flow rate out from the jam ($q_{out} \approx 1900$ vehicles $h^{-1}$ for the left lane) is considerably lower than the flow rate in free flow, i.e., free flow is in a metastable state with respect to the jam emergence (at least in the interval 06:35–06:55).

(iv) It turns out that other local perturbations of the vehicle speed (dotted down arrows 2–4, D21, figure 2(*b*)) which have occurred in this metastable free flow do *not* lead to jam emergence, although their amplitudes would be high enough to cause the F $\rightarrow$ S transition at on-ramps and away from bottlenecks at the same flow rates [7,8]. This also confirms the supposition that the critical amplitude of a local perturbation needed to cause the F $\rightarrow$ J transition should be much higher than that needed to cause the F $\rightarrow$ S transition.

(v) The flow rate on the right lane gradually spatially increases and consequently on the other (especially left) lanes decrease from the detectors D19 to D22, i.e., when vehicles are approaching the off-ramp (the flow rate in the right lane is on average 1180 vehicles $h^{-1}$ at D19 and 2030 vehicles $h^{-1}$ at D22 during the period 06:35–06:55). Almost all vehicles in the right lane at D22 leave the highway via the off-ramp (the average flow rate on D23-off is 2010 vehicles $h^{-1}$): the flow in the right lane downstream of D22 and on the off-ramp could be considered as a traffic flow on a one-lane road. This may explain why at 06:41 (dotted up arrow, D22, figure 2(*b*), left), in contrast to the sharp speed decrease in the right lane, the other lanes display only a very small decrease in speeds. On the other hand, if such a decrease in speed in the right lane at on-ramps or away from bottlenecks is realized, the F $\rightarrow$ S transition usually occurs [7,8]. However, in the vicinity of an off-ramp, only those vehicles which want to continue on the freeway may change away from the right lane. In our example, this fraction is negligible. As a result, the F $\rightarrow$ S transition at the off-ramp is hindered and therefore the F $\rightarrow$ J transition occurs.

The observations made allow us to propose the following: (i) the F $\rightarrow$ J transition is possible *only if* the F $\rightarrow$ S transition is hindered due to a non-homogeneity, in particular at a traffic split on a highway. Such a case is realized at an off-ramp, if a high enough flow of vehicles leave a highway via an off-ramp. In these cases, even if free flow is in a metastable state with respect to jam emergence, only perturbations of very high amplitude may cause the F $\rightarrow$ J transition. (ii) At on-ramps and away from bottlenecks the F $\rightarrow$ J transition does not occur: jam(s) emerge due to the sequence of the F $\rightarrow$ S $\rightarrow$ J transitions as described in [8]. In these cases the existence of the maximum point of free flow is linked to the F $\rightarrow$ S transition.

All known traffic flow models which claim to show jam emergence reach maximum

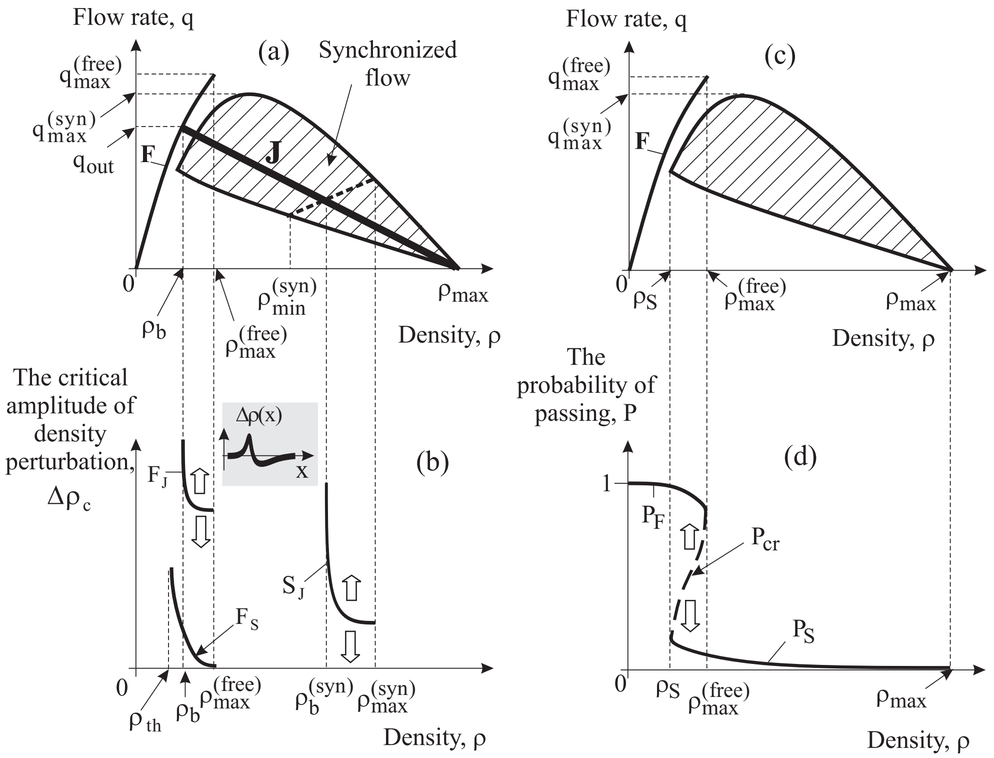


**Figure 4.** A qualitative explanation of the phase transitions [5, 8, 9, 12]: (*a*) a schematic concatenation of states of free flow (curve F) and of homogeneous (steady speed) states of synchronized flow (the hatched region which is the same as in figure 3) with the line J, i.e. the characteristic line for the downstream front of a wide moving jam [6]. (*b*) Qualitative dependences of the critical amplitude of a density local perturbation on the density: for the F → S transition (curve $F_S$), for the F → J transition (curve $F_J$), and for the S → J transition (curve $S_J$). The latter transition is related to synchronized flows with a given vehicle speed (homogeneous-in-speed states, dotted line in (*a*)). (*c*), (*d*) The minimum density in synchronized flow $\rho_S$ (*c*) and a qualitative dependence of the mean probability of the overtaking, $P$, on the density (*d*). It has been proposed that (i) the critical amplitude of a local perturbation is a finite value at thresholds of the phase transitions ($\rho_{\rm th}$, $\rho_b$ ($\rho_b = \rho_{\rm min}$, where the density $\rho_{\rm min}$ is related to the flow rate out from a wide jam, $q_{\rm out}$) and $\rho_b^{\rm (syn)}$, respectively for the F → S, the F → J and the S → J transitions) and (ii) the critical amplitude of a local perturbation needed to cause the S → J transition (curve $S_J$) should be considerably lower than that needed to cause the F → J transition (curve $F_J$).

free flow at the density where the critical amplitude of the F → J transition is zero (e.g. [14]). However, the traffic of our experiments cannot get to this point since the F → S transition happens at a lower density. The experimental results presented in [8, 13] are also in contradiction to model results of traffic phenomena at on-ramps [15]. Note that one of the basic assumptions of traffic flow models and theories is the existence of the fundamental diagram for hypothetical homogeneous and stationary states of traffic flow (e.g. [14, 15]). However, experimental results allow us to suggest that there are *no* fundamental diagrams which may describe the whole multitude even of homogeneous (steady) states of synchronized flow [6–9]. This might be one of the main reasons why traffic flow models cannot predict and explain phase transitions in traffic flow discovered in [7–9].

Recently Kerner proposed alternative hypotheses to the theory of traffic flow [5, 8, 9, 12] which may qualitatively explain experimental conclusions made in [6–9] and in this paper.

(1) The whole multitude of hypothetical homogeneous and stationary (steady) states of synchronized flow is related to a two-dimensional region in the flow–density plane. This region is the same for a multi-lane road and for a one-lane road (hatched regions, figure 3). The whole multitude of non-homogeneous and non-stationary states of synchronized flow is also related to approximately the same two-dimensional region. However, it must be noted that usually only a fraction of this multitude of states of synchronized flow is realized in *each specific case* (see, e.g., figure 3(*c*) in [7]). (Note that homogeneous and stationary states of synchronized flow cannot exists in the vicinity of the jam density $\rho_{\mathrm{max}}$, exactly if the vehicle speed is lower than some minimal possible vehicle speed $v_{\mathrm{min}}^{(\mathrm{syn})}$ (figure 3) which may be about 5–10 km h$^{-1}$. Therefore, the related points on hatched regions in figure 3 should be excepted.)

(2) All hypothetical homogeneous and stationary (steady) states of traffic flow are stable with respect to infinitesimal perturbations.

(3) There are two qualitatively different kinds of nucleation effect in homogeneous (steady) states of traffic flow:

  (a) The nucleation effect which is responsible for the jam's formation, i.e., for the F $\rightarrow$ J transition and the S $\rightarrow$ J transition (figures 4(*a*) and (*b*)).

  (b) The nucleation effect which is responsible for the F $\rightarrow$ S transition (figures 4(*c*) and (*d*)).

(4) At each given density in homogeneous states of free flow the critical amplitude of a local perturbation of traffic variables (density or/and vehicle speed) which is needed for the realization of the F $\rightarrow$ S transition (curve $\mathrm{F_S}$ in figure 4(*b*)) is considerably lower than the critical amplitude of a local perturbation which is needed for the realization of the F $\rightarrow$ J transition (curve $\mathrm{F_J}$ in figure 4(*b*)); respectively, the probability of the F $\rightarrow$ S transition is considerably higher than the F $\rightarrow$ J transition.

(5) The F $\rightarrow$ S transition is related to a jump change in the mean value of the probability of overtaking, $P$. This probability is described by a Z-shaped curve in the flow–density plane (figure 4(*d*)).

(6) The line J in figure 4(*a*) determines the threshold of the jam's existence and excitation: all (*an infinite number!*) homogeneous states of traffic flow which are related to the line J in the flow–density plane are *threshold states* with respect to the jam's formation. The line J separates all homogeneous states of both free and synchronized flow into two qualitatively different classes:

  (a) In states which are related to points in the flow–density plane lying below (see axes in figure 4(*a*)) the line J *no* moving jams either can continue to exist or can be excited.

  (b) States which are related to points in the flow–density plane lying on and above the line J are *metastable states* with respect to the jam's formation where the related nucleation effect and consequently either the F $\rightarrow$ J transition or the S $\rightarrow$ J transition can be realized.

  The critical amplitude of the local perturbations is maximal at the line J and depends both on the density and on the flow rate above the line J.

An explanation and a more detailed consideration of the hypotheses can be found in [5,8,9,12].

Due to the occurrence of a local perturbation of traffic variables whose amplitude exceeds some critical amplitude $\Delta\rho_c$ (curve $\mathrm{F_S}$, figure 4(*b*)), the probability of overtaking in free flow falls below the critical probability of overtaking (dotted curve $P_{\mathrm{cr}}$, figure 4(*d*)). Then, corresponding to item (5), the probability of overtaking will continue to decrease in an avalanche-like manner and the F → S transition will occur in this local region (down arrow in figure 4(*d*)). However, if a perturbation occurs on the right lane near an off-ramp and most vehicles have to remain in this lane, then the probability of overtaking does not decrease in an avalanche-like manner in the other lanes. This may explain why the F → S transition does not occur even if the amplitude of the perturbation is high (figure 2(*b*), D22, dotted up arrow).

Because the critical probability of overtaking, $P_{cr}$, merges with the value $P_F$ for free flow at the maximum density in free flow, $\rho_{max}^{(free)}$ (figure 4(*d*)), the critical amplitude $\Delta\rho_c$ on the curve $F_S$ reaches *zero* at this maximum point. This means that a density local perturbation of even small amplitude in free flow causes the F → S transition at the maximum density in free flow $\rho_{max}^{(free)}$. Therefore, the existence of this limit point of free flow is linked to the F → S transition rather than the F → J transition.

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