Chapter 2
Definitions of The Three Traffic Phases

2.1 Traffic Variables, Parameters, and Patterns

Traffic flow phenomena are associated with a complex dynamic behavior of spatiotemporal traffic patterns. The term *spatiotemporal* reflects the empirical evidence that traffic occurs in *space and time*. Therefore, only through a *spatiotemporal* analysis of real measured traffic data the understanding of features of real traffic is possible. In other words, spatiotemporal features of traffic can only be found, if traffic variables are measured in real traffic in space and time.

The term a *spatiotemporal traffic pattern* (traffic pattern for short) is defined as follows:

- A spatiotemporal traffic pattern is a distribution of traffic flow variables in space and time.

Examples of traffic variables are the flow rate q [vehicles/h], vehicle density ρ [vehicles/km], and vehicle speed v [km/h] or [m/s] (see, e.g., [1–3]).

The term *empirical* features of a spatiotemporal traffic pattern means that the features are found based on an analysis of real measured traffic data.

A spatiotemporal traffic pattern is limited spatially by pattern fronts. There are downstream and upstream fronts of a traffic pattern. The downstream pattern front separates the pattern from other traffic patterns downstream. The upstream pattern front separates the pattern from other traffic patterns upstream.

The term *front of traffic pattern* is defined as follows:

- A front of a traffic pattern is either a moving or motionless region within which one or several of the traffic variables change abruptly in space (and in time, when the front is a moving one).

Traffic variables and traffic patterns can depend considerably on *traffic parameters*.

- Traffic parameters are parameters, which can influence traffic variables and traffic patterns.

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Examples of traffic parameters are a traffic network infrastructure (including, e.g., highway bottleneck types and their locations), weather (whether the day is sunny or rainy or else foggy, dry or wet road, or even ice and snow on road), percentage of long vehicles, day time, working day or week-end, other road conditions, and vehicle technology.

Considering traffic flow patterns, we distinguish between *macroscopic* and *microscopic* descriptions of the patterns.

In the macroscopic pattern description, the behavior of macroscopic measured traffic variables and macroscopic characteristics of traffic flow patterns in space and time should be studied and understood.

Examples of the macroscopic traffic variables are the flow rate, vehicle density, occupancy, and average vehicle speed (see, e.g., [1–3]).

An example of macroscopic characteristics of a traffic pattern is the mean velocities of the downstream and upstream fronts of the pattern. We see that the macroscopic traffic variables and pattern characteristics are associated with an averaging behavior of many vehicles in traffic, i.e., the variables and characteristics are averaged during an averaging time interval for traffic variables denoted by T_{av}.

As an example of the term an *averaging time interval for traffic variables*, we consider *1-min average data* that means the following: all macroscopic traffic variables associated with a traffic pattern under consideration are averaged with the use of the same averaging time interval $T_{\text{av}} = 1$ min.

In contrast with the macroscopic description of traffic patterns, the microscopic description of traffic flow patterns is associated with a study of microscopic traffic variables and microscopic pattern characteristics that reflect the behavior of individual (called also *single*) vehicles in traffic flow.

Examples of the microscopic traffic flow variables are single vehicle space coordinates and their time-dependence, a time headway (net time distance) τ [s] and a space gap (net distance) g [m] between two vehicles following each other (Fig. 2.1), a single vehicle speed v [km/h] or [m/s], a vehicle length d [m] [1–3]. In particular, vehicle space coordinates and their time-dependence can be used for the reconstruction of vehicle trajectories, i.e., the trajectories of vehicles in the space–time plane[1]. Note that measured traffic data in which microscopic traffic variables can be identified are also called *single vehicle data*[2].

There are many measurement techniques of traffic flow variables based on road detectors (see, e.g., [1–3]), video camera measurements (see, e.g., [4]), etc. We briefly discuss measurements of traffic variables with induction double loop detectors installed at some road locations.

Each detector consists of two induction loops spatially separated by a given small distance ℓ_{d} (Fig. 2.1). The induction loop registers a vehicle moving on the road by producing a pulse electric current that begins at some time t_{b} when the vehicle reaches the induction loop and it ends some time later t_{f} when the vehicle leaves the

[1] An example of empirical vehicle trajectories is shown in Fig. 2.3 of Sect. 2.2.1.

[2] Naturally, there is also an intermediate description of traffic called as a *mesoscopic* description of traffic phenomena in which both macroscopic and microscopic traffic flow variables and/or characteristics of traffic patterns are studied.

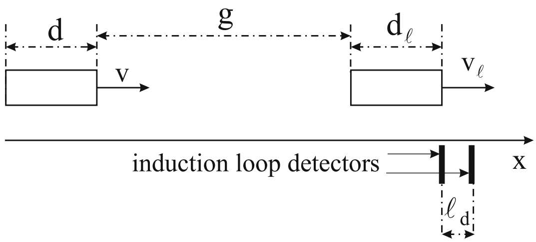

Fig. 2.1 Qualitative scheme of induction loop detector measurements

induction loop. The duration of this current pulse

$$\Delta t = t_{\mathrm{f}} - t_{\mathrm{b}} \tag{2.1}$$

is therefore related to the time taken by the vehicle to traverse the induction loop.

Every vehicle that passes the induction loop produces a related current pulse. This enables us to calculate the gross time gap between the vehicle with a speed v and the preceding vehicle with a speed v_ℓ that have passed the induction loop one after the other:

$$\tau^{(\mathrm{gross})} = t_{\mathrm{b}} - t_{\ell,\,\mathrm{b}}, \tag{2.2}$$

where subscript ℓ is related to the preceding vehicle (Fig. 2.1). We can further calculate the flow rate q as the measured number of vehicles N passing the induction loop during a given averaging time interval for traffic variables T_{av}:

$$q = \frac{N}{T_{\mathrm{av}}}. \tag{2.3}$$

Because there are two different induction loops in each detector, separated by a known distance ℓ_{d} from one another, the detector is able to measure the individual vehicle speed. Indeed, due to the distance ℓ_{d} between two loops of the detector, the first (upstream) loop registers the vehicle earlier than the second (downstream) one. Therefore, if the vehicle speed v is not zero, there will be a time lag δt between the current pulses produced by the two detector induction loops when the vehicle passes both. It is assumed that by virtue of the small value of ℓ_{d}, the vehicle speed does not change between the induction loops. This enables us to calculate the single (individual) vehicle speed v:

$$v = \frac{\ell_{\mathrm{d}}}{\delta t} \tag{2.4}$$

and the vehicle length d

$$d = v\Delta t. \tag{2.5}$$

From Eqs. (2.2) and (2.5) it is possible to calculate the time headway:

$$\tau = \tau^{(\mathrm{gross})} - \frac{d_\ell}{v_\ell}. \tag{2.6}$$

At a given time instant $t = t_1$, the time headway between vehicles $\tau(t_1)$ is *defined* as a time it takes for a vehicle to reach a road location at which the bumper of the preceding vehicle is at the time instant t_1. In single vehicle data measured at a road detector (Fig. 2.1), t_1 is the time at which the preceding vehicle leaves the detector whose location is therefore related to the location of the bumper of the preceding vehicle in the time headway definition; the time headway is equal to $\tau(t_1) = t_2 - t_1$, where t_2 is the time at which the vehicle front has been recorded at the detector. The time headway τ in (2.6) is related to the time instant t_1.

Single vehicle speeds also enable us to calculate the average (arithmetic) vehicle speed v of N vehicles passing the detector in time interval $T_{\rm av}$,

$$v = \frac{1}{N}\sum_{i=1}^{N} v_i, \tag{2.7}$$

where index $i = 1, 2, ..., N$.

The vehicle density (the number of vehicles per unit length of a road, e.g., vehicles per km) can be roughly estimated from the relation

$$\rho = \frac{q}{v}, \tag{2.8}$$

where v is the average speed. However, it should be noted that the vehicle density ρ is related to vehicles on a road section of a given length whereas the vehicle speed is measured at the location of the detector only and is averaged over the averaging time interval $T_{\rm av}$. As a result, at low average vehicle speeds, the vehicle density estimated via (2.8) can lead and does usually lead to a considerable discrepancy in comparison with the real vehicle density. For a more detailed consideration of the criticism of measured data analyses associated with a considerably error in the density estimation with formula (2.8) see [5] and a recent review [6].

A road detector can also measure a macroscopic traffic variable called *occupancy*, which is defined through the formula (e.g., [1]):

$$o = \frac{T_{\rm veh}}{T_{\rm av}} 100\%, \tag{2.9}$$

where $T_{\rm veh}$ is the sum of the time intervals when the detector has measured vehicles during the time interval $T_{\rm av}$:

$$T_{\rm veh} = \sum_{i=1}^{N} \Delta t_i, \tag{2.10}$$

Δt_i is defined via (2.1).

2.2 Free Flow (F) and Congested Traffic

2.2.1 Definition of Congested Traffic

Free traffic flow (free flow for short) is usually observed, when the vehicle density in traffic is small enough. At small enough vehicle density, interactions between vehicles in free flow are negligible. Therefore, vehicles have an opportunity to move with their desired maximum speeds (if this speed is not restricted by road conditions or traffic regulations).

When the density increases in free flow, the flow rate increases too, however, vehicle interaction cannot be neglected any more. As a result of vehicle interaction in free flow, the average vehicle speed decreases with increase in density.

To illustrate these well-known features [1–3], the flow rate and density, which is calculated with formula (2.8) from the flow rate and average speed measured at a road location, are presented in the flow–density plane (points left of a dashed line FC in Fig. 2.2 (a)). In empirical traffic data, the increase in the flow rate with the density increase in free flow has a limit. At the associated *limit (maximum) point of free flow*, the flow rate and density reach their maximum values denoted by $q_{\max}^{(\text{free, emp})}$ and $\rho_{\max}^{(\text{free, emp})}$, respectively, while the average speed has a minimum value for the free flow:

$$v_{\min}^{(\text{free, emp})} = q_{\max}^{(\text{free, emp})} / \rho_{\max}^{(\text{free, emp})}. \qquad (2.11)$$

These points are well-fitted by a flow–density relationship for free flow, i.e., a certain curve with a positive slope between the flow rate and density associated with averaging of measured data shown left of the dashed line FC in Fig. 2.2 (a) to one average flow rate for each density (curve F in Fig. 2.2 (b)) [1–3, 7, 8]. This flow–density relationship is called the fundamental diagram of free flow. The empirical fundamental diagram of free flow is cut off at the limit point of free flow $(\rho_{\max}^{(\text{free, emp})}, q_{\max}^{(\text{free, emp})})$ (Fig. 2.2 (b)) [1–3, 9].

To distinguish free flow points in the flow–density plane, we use in Fig. 2.2 (a, b) the dashed line FC between the origin of the flow–density plane and the limit point of free flow; the slope of the line FC is equal to the minimum speed in free flow $v_{\min}^{(\text{free, emp})}$ (2.11). Thus empirical points of free flow as well as the associated fundamental diagram lie to the left of the dashed line FC in the flow–density plane.

In empirical observations, when density in free flow increases and becomes great enough, the phenomenon of the onset of congestion is observed in this free flow: the average speed decreases abruptly to a lower speed in congested traffic:

- Congested traffic is defined as a state of traffic in which the average speed is *lower* than the minimum average speed that is still possible in free flow (e.g., [3, 10]).

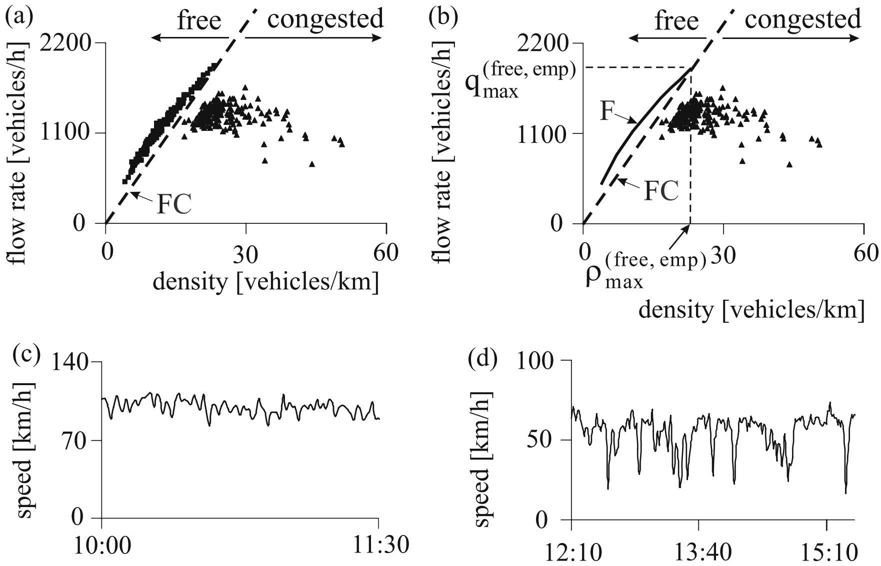

Fig. 2.2 Free flow and congested traffic (e.g., [1–3, 9, 10]). (a) Empirical data for free flow (points left of the dashed line *FC*) and for congested traffic (points right of the dashed line *FC*). (b) The fundamental diagram for free flow (curve *F*) and the same measured data for congested traffic as those in (a). (c, d) Vehicle speed in free flow (c) and congested traffic (d), related to points left and right of the line *FC* in (a), respectively. 1-min average data measured at a road location

Thus empirical points of congested traffic lie to the right of the dashed line *FC* in the flow–density plane[3].

Traffic congestion occurs mostly at a highway bottleneck (bottleneck for short). The bottleneck can be a result of road works, on- and off-ramps, a decrease in the number of road lanes, road curves and road gradients, bad weather conditions, accidents, etc. [1–3].

In congested traffic, a great variety of congested traffic patterns are observed [10–16]. A *congested traffic pattern* (congested pattern for short) is defined as follows.

- A congested traffic pattern is a spatiotemporal traffic pattern within which there is congested traffic. The congested pattern is separated from free flow by the downstream and upstream fronts: At the downstream front, vehicles accelerate

[3] It must be noted that the definition of congested traffic through the use of the empirical limit point on the fundamental diagram of free flow seems to be easy, however, can lead to an error in measurements of the minimum speed that is possible in free flow. This is because the exact value of this minimum speed that is possible in free flow is associated with the maximum (limit) flow rate $q_{\max}^{(\text{free, emp})}$ in free flow at which probability of traffic breakdown is equal to one (see explanations of the flow rate dependence of breakdown probability in Sect. 4.2.2). However, it is extremely difficult to find such a free flow in real measured traffic data. This comment is also related to the limit point for free flow shown in Fig. 2.2: the speed $v_{\min}^{(\text{free, emp})}$ associated with this limit point for free flow gives only an approximate value for the minimum speed that is possible in free flow.

from a lower speed within the pattern to a higher speed in free flow downstream; at the upstream front, vehicles decelerate from a free flow speed to a lower speed within the congested pattern.

In particular, one of the congested traffic patterns is a moving traffic jam [10–16]. A *moving traffic jam* (moving jam for short) is defined as follows:

- A moving jam is a localized congested traffic pattern that moves upstream in traffic flow (Fig. 2.3). Within the moving jam the average vehicle speed is very low (sometimes as low as zero), and the density is very high. The moving jam is spatially restricted by the downstream jam front and upstream jam front. Within the downstream jam front vehicles accelerate from low speed states within the jam to higher speeds in traffic flow downstream of the moving jam. Within the upstream jam front vehicles must slow down to the speed within the jam. Both jam fronts move upstream. Within the jam fronts the vehicle speed, flow rate, and density vary abruptly.

Moving jams have been studied empirically by many authors, in particular, in classic empirical works by Edie *et al.* [11–14], Treiterer *et al.* [15, 16] (Fig. 2.3), and Koshi *et al.* [10].

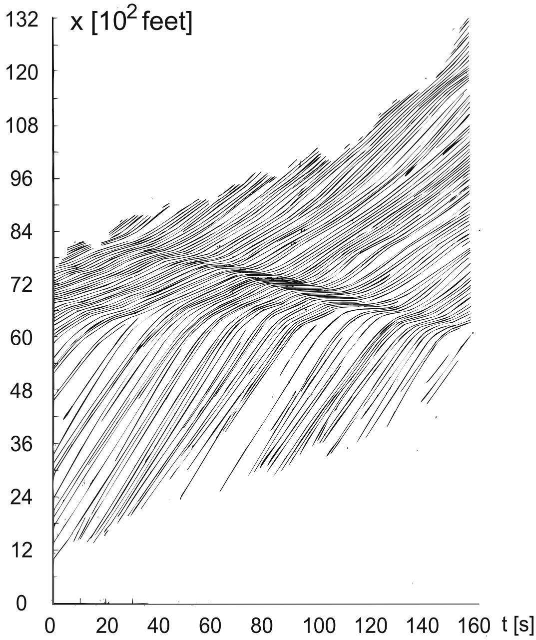

Fig. 2.3 A moving jam: dynamics of vehicle trajectories derived from aerial photography (1 feet is equal to 0.3048 m). Each of the curves in this figure shows a vehicle trajectory in the time–space plane. Taken from Treiterer [16]

2.2.2 *Traffic Breakdown*

The onset of congestion in an initial free flow is accompanied by a abrupt decrease in average vehicle speed in the free flow to a considerably lower speed in congested traffic (Figs. 2.4 and 2.5). This speed breakdown occurs mostly at highway bottlenecks and is called the breakdown phenomenon or traffic breakdown (see [9, 17–21] and earlier works referred to in the book [1] and in Chap. 2 written by Hall in [3]).

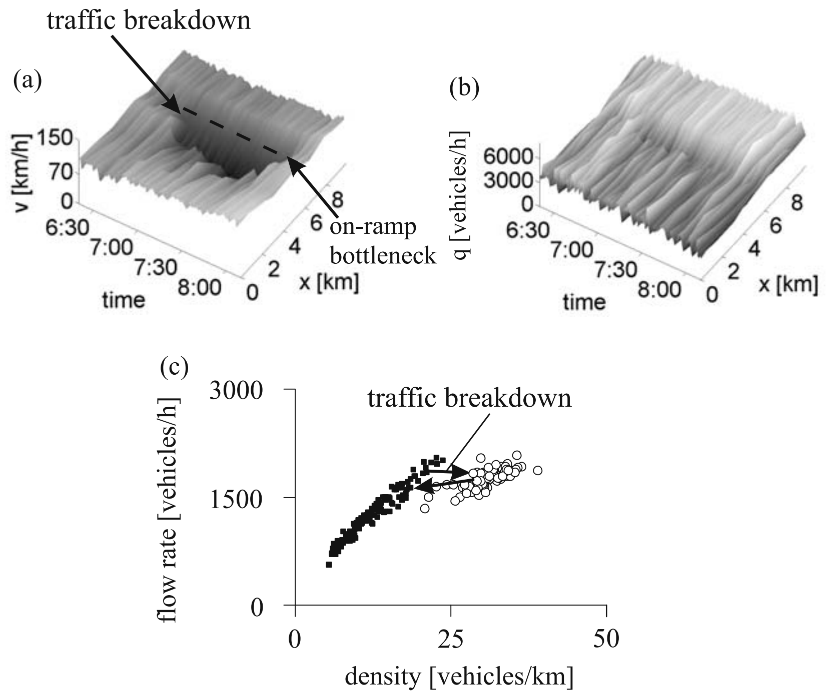

Fig. 2.4 Empirical example of traffic breakdown and hysteresis effect at on-ramp bottleneck: (a, b) Average speed (a) and flow rate (b) on the main road in space and time (note that the flow rate increase downstream of the bottleneck seen in (b) is associated with the on-ramp inflow). (c) Hysteresis effect in the flow–density plane labeled by two arrows representing traffic breakdown and return transition from congested traffic to free flow. 1-min average data. This example of traffic breakdown is qualitatively the same as many other examples observed in various countries (e.g., [9, 17–21])

The flow rate in free flow downstream of a bottleneck measured just before traffic breakdown occurs is called the *pre-discharge flow rate*. The flow rate in free flow downstream of a bottleneck after traffic breakdown has occurred at this bottleneck, i.e., the flow rate in the congested pattern outflow is called the *discharge flow rate* [17].

Hall and Agyemang-Duah have found [17] that

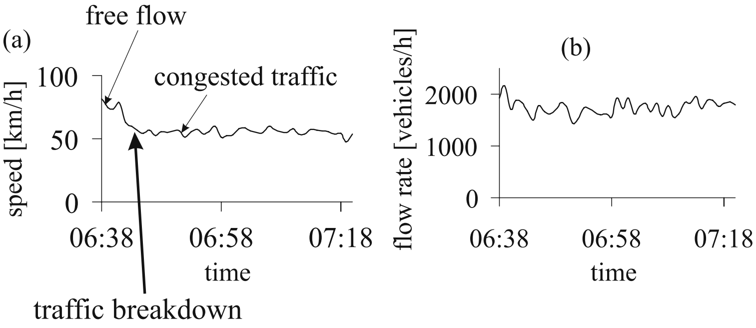

Fig. 2.5 Traffic breakdown at on-ramp bottleneck. Vehicle speed (a) and flow rate downstream of the bottleneck (b) as functions of time related to Fig. 2.4 (e.g., [9, 17–19])

- the discharge flow rate can be as great as the pre-discharge flow rate: in some cases, the discharge flow rate is smaller, however, in other cases it is greater than the pre-discharge flow rate.

2.2.3 Probabilistic Features of Traffic Breakdown

In 1995, Elefteriadou *et al.* found that traffic breakdown at a bottleneck has a probabilistic nature [18]. This means the following: at a given flow rate in free flow downstream of the bottleneck traffic breakdown can occur but it should not necessarily occur. Thus on one day traffic breakdown occurs, however, on another day at the same flow rates traffic breakdown is not observed.

Persaud *et al.* found [19] that empirical probability of traffic breakdown at a bottleneck is an increasing flow rate function (Fig. 2.6). Later such an empirical probability of traffic breakdown was also found on different highways in various countries [22–27].

Another empirical probabilistic characteristic of traffic breakdown is as follows. At given traffic parameters (weather, etc.), the flow rate downstream of an on-ramp bottleneck associated with the empirical maximum flow rate in free flow $q_{\text{max}}^{(\text{free, emp})}$, which was measured on a specific day before congestion occurred, can be greater than the pre-discharge flow rate denoted by $q_{\text{FS}}^{(\text{B})}$ in Fig. 2.7.

After traffic breakdown has occurred, the emergent congested pattern shown in Fig. 2.4 (a, b) exists for about one hour at the bottleneck: at 7:40 free flow occurs at the bottleneck. This restoration of free flow is related to a reverse transition from congested traffic to the free flow at the bottleneck. Traffic breakdown and the reverse transition are accompanied by a well-known *hysteresis effect* and hysteresis loop in the flow–density plane: a congested pattern emerges usually at a greater flow rate downstream of the bottleneck than this flow rate is at which the congested pattern dissolves (see references in [9, 17, 20, 21]) (Fig. 2.4 (c)).

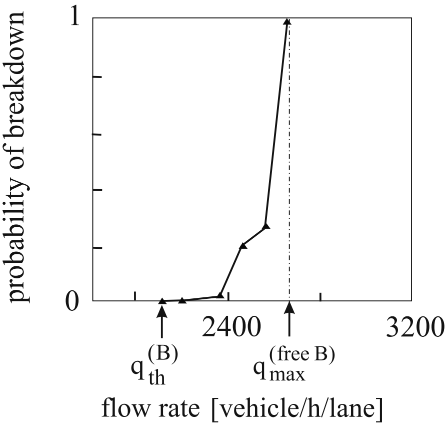

Fig. 2.6 Probability for traffic breakdown at an on-ramp bottleneck for $T_{av} = 10$ min. Taken from Persaud *et al.* [19]. Explanations of characteristic flow rates $q_{th}^{(B)}$ and $q_{max}^{(free\ B)}$ added by the author appears in Sect. 3.3.3

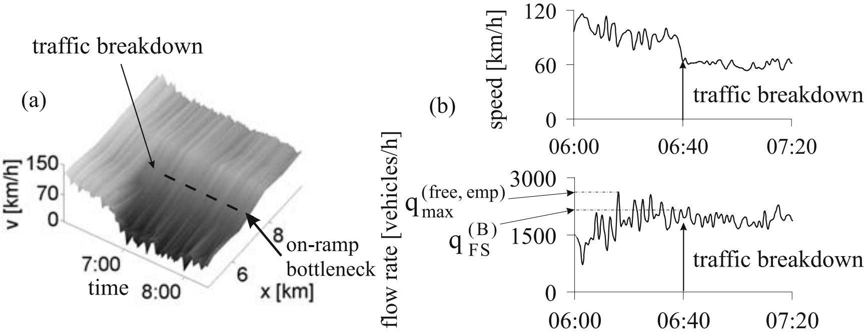

Fig. 2.7 Empirical example in which the flow rate in free flow downstream of on-ramp bottleneck at which traffic breakdown occurs, i.e., the pre-discharge flow rate denoted by $q_{FS}^{(B)}$ is smaller than $q_{max}^{(free,\ emp)}$: (a) Average speed on the main road in space and time. (b) Speed and flow rate (per lane) averaged across the road at location about 100 m downstream of the end of the on-ramp merging region. Up-arrows in (b) show the time instant of the breakdown labeled by “traffic breakdown”. The on-ramp bottleneck is the same as that in Fig. 2.4. 1-min average data

2.3 Methodology of Three-Phase Traffic Theory

Three-phase traffic theory introduced by the author [28–36] is a qualitatively theory based on *common* spatiotemporal features of measured (empirical) congested traffic patterns[4]. The methodology of three-phase traffic theory is as follows.

[4] A methodology of measurements of congested patterns and their study have been discussed in Sect. 2.4.11 of the book [36].

1) Spatiotemporal measurements of traffic flow variables on different highways in various countries over many days and years are collected and analyzed under a variety of traffic parameters.
2) Congested traffic patterns are identified in these measurements.
3) Common qualitative spatiotemporal features of these measured congested traffic patterns are identified [5, 28–40]. There are two main approaches for the classification of the common qualitative spatiotemporal pattern features presented in item 4) and 5) below, respectively.
4) Common pattern features are qualitatively the same *independent of traffic parameters*, i.e., they are qualitatively the same on different highways in various countries over many days and years of measurements *and* they are qualitatively the same for different network infrastructure and highway bottleneck types, weather, percentage of long vehicles, other road conditions, and vehicle technology. Moreover, these common spatiotemporal pattern features must be qualitatively independent of day time, working day or week-end, whether the day is sunny or rainy or else foggy, dry or wet road, or even ice and snow on road, etc.

- Macroscopic and microscopic criteria for traffic phases of three-phase traffic theory (Sects. 2.4–2.6) are some of these common qualitative spatiotemporal features of the measured congested traffic patterns.

5) Common pattern features are qualitatively the same only for a class of congested patterns associated with *a particular set of traffic parameters*. An example of such a class of congested patterns with common qualitative spatiotemporal features are congested patterns at heavy bottlenecks caused by, e.g., bad weather conditions or heavy road works (Sect. 7.2.5).

- An empirical congested traffic pattern classification of Sect. 2.4.6 and Chap. 7 presents some of congested traffic patterns with common qualitative spatiotemporal features[5].

6) The spatiotemporal criteria for the traffic phases and empirical congested traffic pattern classification are the empirical basis for hypotheses of three-phase traffic theory (Chaps. 3–6).

[5] A more detailed classification of common qualitative spatiotemporal pattern features can be found in part II of the book [36] and in [38].

2.4 Two Traffic Phases in Congested Traffic: Wide Moving Jam (J) and Synchronized Flow (S)

2.4.1 Empirical Macroscopic Criteria for defining Phases in Congested Traffic

A traffic phase is a traffic state considered in space and time that possesses some unique *empirical spatiotemporal* features. A traffic state is characterized by a particular set of statistical properties of traffic variables.

Three-phase traffic theory assumes that besides the free flow traffic phase there are two other traffic phases in congested traffic: *synchronized flow* and *wide moving jam*. Thus there are three traffic phases in three-phase traffic theory:

Free flow
Synchronized flow
Wide moving jam

The synchronized flow and wide moving jam phases in congested traffic are defined through the use of the following *macroscopic empirical (objective) criteria* for the traffic phases in congested traffic [28–36]:

[J] The wide moving jam phase is defined as follows. A wide moving jam is a moving jam that maintains the mean velocity of the downstream front of the jam as the jam propagates. Vehicles accelerate within the downstream jam front from low speed states (sometimes as low as zero) inside the jam to higher speeds downstream of the jam. A wide moving jam maintains the mean velocity of the downstream jam front, even as it propagates through other different (possibly very complex) traffic states of free flow and synchronized flow or highway bottlenecks. This is a characteristic feature of the wide moving jam phase.

[S] The synchronized flow phase is defined as follows. In contrast to the wide moving jam traffic phase, the downstream front of the synchronized flow phase does *not* maintain the mean velocity of the downstream front. In particular, the downstream front of synchronized flow is often *fixed* at a bottleneck. In other words, the synchronized flow traffic phase does not show the characteristic feature [J] of the wide moving jam phase.

The downstream front of synchronized flow separates synchronized flow upstream from free flow downstream. Within the downstream front of synchronized flow vehicles accelerate from lower speeds in synchronized flow upstream of the front to higher speeds in free flow downstream of the front.

Thus the definitions of the traffic phases in congested traffic are made via the spatiotemporal macroscopic empirical criteria [J] and [S]. The definitions [J] and [S] are associated with dynamic behavior of the downstream front of these phases, while a wide moving jam or synchronized flow propagates through other traffic states or bottlenecks.

The definitions [J] and [S] of the traffic phases in congested traffic mean that if a congested traffic state is not related to the wide moving jam phase, then the state is associated with the synchronized flow phase. This is because congested traffic can be either within the synchronized flow phase or within the wide moving jam phase. In other words, if in measured data congested traffic states associated with the wide moving jam phase have been identified, then with certainty all remaining congested states in the data set are related to the synchronized flow phase.

2.4.2 Traffic Breakdown at Bottleneck: F→S Transition

Firstly, we apply the phase definitions [S] and [J] to traffic breakdown at the on-ramp bottleneck shown in Fig. 2.5 (a). We see that traffic breakdown leads to congested traffic whose downstream front is fixed at the bottleneck (dashed line in Fig. 2.4 (a)). Thus the congested traffic resulting from traffic breakdown satisfies the definition [S] for the synchronized flow phase.

This is a *common result of all empirical observations of traffic breakdown at any highway bottlenecks*: traffic breakdown is associated with a phase transition from free flow to synchronized flow (F→S transition for short):

- The terms *F→S transition*, *breakdown phenomenon*, *traffic breakdown*, and *speed breakdown* are synonyms related to the same effect: the onset of congestion in free flow.

2.4.2.1 Effectual Bottleneck and its Effective Location

Traffic breakdown (F→S transition) occurs usually at the same highway bottlenecks of a road section. These bottlenecks are called *effectual bottlenecks*.

- An effectual bottleneck is a bottleneck at which traffic breakdown most frequently occurs on many different days.

An example of an effectual bottleneck is the on-ramp bottleneck shown in Fig. 2.5 (a). After the breakdown has occurred, synchronized flow is forming at the bottleneck.

- A road location in a neighborhood of the bottleneck at which the downstream front of synchronized flow is fixed is called an *effective location of the effectual bottleneck* (effective location of bottleneck for short).

It must be noted that the effective location of the bottleneck can be different from the location at which traffic breakdown, i.e., F→S transition has occurred leading to congested pattern emergence. Moreover, both the location of traffic breakdown and the effective location of the bottleneck are probabilistic values in real traffic. Even for the same type of congested pattern the effective location of the bottleneck can randomly change over time [36].

2.4.2.2 Flow Rate in Synchronized Flow

The discharge flow rate, i.e., the flow rate in the congested pattern outflow can be as great as the pre-discharge flow rate. This empirical result is associated with a common feature of empirical observations of synchronized flow that during traffic breakdown the flow rate in the emergent synchronized flow at the location of traffic breakdown can be almost as great as the flow rate in free flow has been before traffic breakdown at the bottleneck has occurred. An example can be seen in Fig. 2.5 (b): whereas there is an abrupt decrease in average vehicle speed, the flow rate does not necessarily abruptly decrease during traffic breakdown (F→S transition) and within an emergent synchronized flow at the bottleneck.

In some cases, the flow rate in synchronized flow, which determines in the most degree the discharge flow rate, can be even greater than the pre-discharge flow rate.

- A common empirical feature of synchronized flow that the flow rate within synchronized flow can be as great as in free flow is the important one for feedback on-ramp metering control applications (Sect. 9.2).

2.4.3 Propagation of Wide Moving Jams through Bottlenecks

In Fig. 2.8, there is a sequence of two moving jams propagating upstream on a road section with a bottleneck. These moving jams propagate through different states of traffic flow and through the bottleneck while maintaining the downstream jam front velocity. Thus in accordance with the definition [J], these moving jams are wide moving jams.

There is congested traffic in which speed is much lower than in free flow (compare vehicle speeds in Fig. 2.8 (c, d)). The downstream front of this congested traffic flow, within which vehicles accelerate to free flow, is fixed at the bottleneck (dashed line in Fig. 2.8 (a)). Therefore, in accordance with the definition [S] this congested traffic is synchronized flow.

We can see that whereas in wide moving jams both the speed and flow rate are very low (sometimes as low as zero), in synchronized flow the flow rate is high (compare the flow rates within the wide moving jams and within synchronized flow in Fig. 2.8 (d)). The vehicle speed in synchronized flow is considerably lower than in free flow. However, as abovementioned the flow rates in the free flow and synchronized flow phases can be close to each other (Fig. 2.8 (c, d)).

2.4.4 Explanation of Terms "Synchronized Flow" and "Wide Moving Jam"

The term *synchronized flow* reflects the following features of this traffic phase:

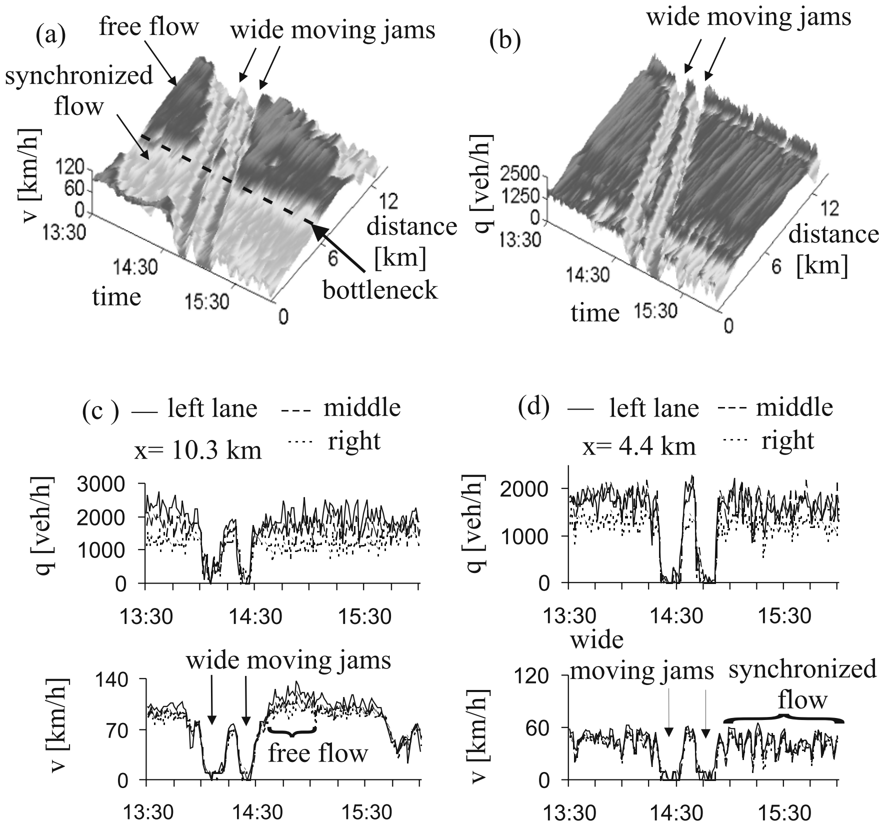

Fig. 2.8 Explanation of the three traffic phases. (a, b) Vehicle speed (a) and flow rate averaged across all road lanes (b) as functions of time and space. (c, d) Flow rate and average vehicle speed at two different freeway locations (c) and (d) in different road lanes. Taken from [36]

(i) It is a continuous traffic flow with no significant stoppage, as often occurs within a wide moving jam. The word *flow* reflects this feature.

(ii) Although in empirical synchronized flow vehicle speeds across different lanes on a multi-lane road should not be necessarily synchronized, there is a *tendency* towards synchronization of these speeds in this flow. In addition, there is a *tendency* towards synchronization of vehicle speeds in each of the road lanes (bunching of vehicles) in synchronized flow. This is due to a relatively small probability of passing in synchronized flow. The word *synchronized* reflects these speed synchronization effects.

The term *wide moving jam* reflects the characteristic feature of the jam to propagate through any other state of traffic flow and through any bottleneck while maintaining the mean velocity of the downstream jam front. The phrase *moving jam* reflects the jam *propagation* as a whole localized structure on a road. To distinguish wide moving jams from narrow moving jams, which do not characteristically maintain the mean velocity of the downstream jam front (see Sect. 2.6.3), we use the term *wide moving jam*. This relates to the fact that if a moving jam has a width (in the longitudinal direction) considerably greater than the widths of the jam fronts, and if the vehicle speed within the jam is zero, the jam always exhibits the characteristic feature of *maintaining* the mean velocity of the downstream jam front[6]. Thus the word *wide* reflects this characteristic jam feature.

2.4.5 Wide Moving Jam Emergence: S→J Transition

Based on an analysis of empirical data measured over many days and years on various freeways it has been found [28, 29] that wide moving jams do not emerge spontaneously in free flow. In contrast, wide moving jams can emerge spontaneously in synchronized flow. Observations show that the greater the density in synchronized flow, the more likely is spontaneous moving jam emergence in that synchronized flow.

A wide moving jam emerges in an initial free flow due to a sequence of two phase transitions [36]:

1) An F→S transition occurs. As a result of this traffic breakdown, synchronized flow emerges.
2) Later and usually at another road location than the location of this F→S transition, a phase transition from synchronized flow to wide moving jam (S→J transition for short) occurs spontaneously leading to wide moving jam emergence. This sequence of phase transitions is called the F→S→J transitions.

This scenario of wide moving jam emergence in real traffic is illustrated in Fig. 2.9 (a): Firstly, an F→S transition occurs (labeled by "traffic breakdown (F→S transition)"). As a result of traffic breakdown, synchronized flow emerges upstream of the bottleneck (labeled by "synchronized flow"). Later and upstream of the location of traffic breakdown, S→J transitions occur in this synchronized flow. Wide moving jams, which have emerged due to these F→S→J transitions, propagate upstream while maintaining the mean velocity of their downstream jam fronts (labeled by "wide moving jams" in Fig. 2.9 (a)).

2.4.6 Definitions of Synchronized Flow and General Congested Patterns

After traffic breakdown, i.e., an F→S transition has occurred at an effectual bottleneck, synchronized flow is formed at the bottleneck. There are two main types of

[6] An explanation of this feature of a wide moving jam can be found in Sect. 7.6.5 of [36].

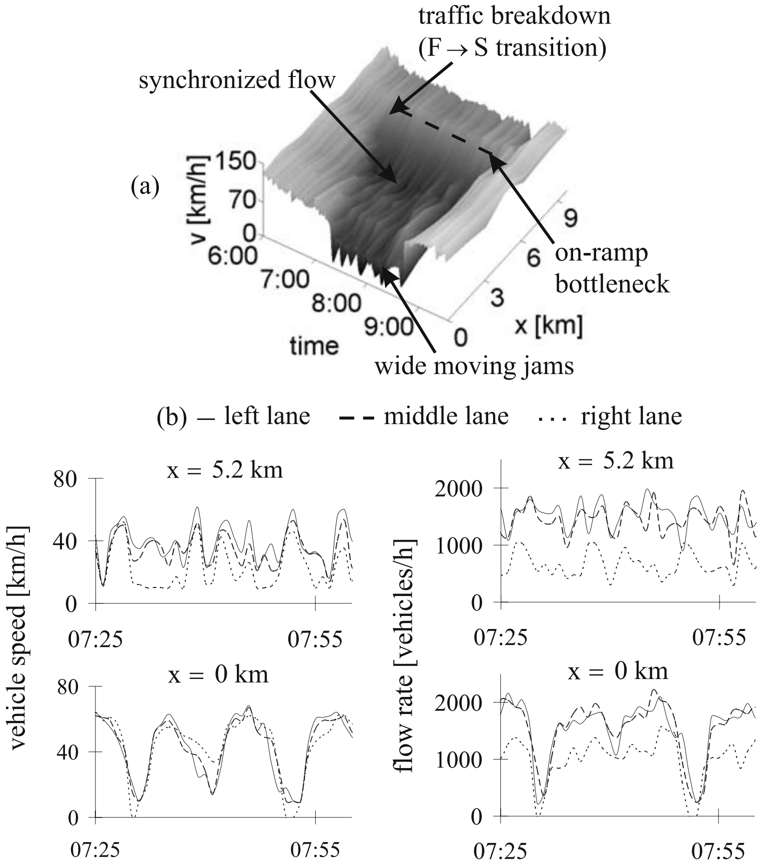

Fig. 2.9 Empirical example of wide moving jam emergence in synchronized flow: (a) Vehicle speed in space and time. (b) Vehicle speed (left) and flow rate (right) in three road lanes within synchronized flow (location 5.2 km) and wide moving jams (location 0 km). 1-min average data. This figure shows the wide moving jam emergence in synchronized flow whose occurrence at the on-ramp bottleneck is shown in Fig. 2.7. Taken from [36]

congested patterns that result from traffic breakdown at the bottleneck: a *synchronized flow traffic pattern* (synchronized flow pattern or SP for short) and a *general congested traffic pattern* (general pattern or GP for short).

The terms *synchronized flow pattern (SP)* and *general pattern (GP)* are defined as follows:

- A synchronized flow pattern (SP) is a spatiotemporal congested traffic pattern in which congested traffic consists only of the synchronized flow traffic phase.

- A general pattern (GP) is a spatiotemporal congested traffic pattern in which congested traffic consists of the synchronized flow and wide moving jam phases[7].

An empirical example of an SP is shown in Fig. 2.4 (a, b). Indeed, this congested traffic pattern consists of only the synchronized flow phase. In contrast, a congested pattern shown in Fig. 2.9 consists of the synchronized flow and wide moving jam phases. Therefore, this pattern is an empirical example of an GP. A more detailed account of SPs and GPs features appears in Chap. 7.

2.5 Characteristic Parameters of Wide Moving Jam Propagation

In a theory of wide moving jam propagation firstly derived in 1994 by Kerner and Konhäuser [41] and in investigations of wide moving jams in real measured traffic data made in [40] have been found that there are characteristic parameters of wide moving jam propagation. The main common feature of the characteristic parameters of wide moving jam propagation is that at given traffic parameters (weather, etc.; see Sect. 2.1) they do not depend on traffic variables in traffic flow upstream of a wide moving jam and they do not change while the jam propagates on a road. These characteristic parameters are the same for different wide moving jams. The jam characteristic parameters are as follows:

(i) The mean velocity of the downstream front of a wide moving jam denoted by v_g. The constancy of v_g while the jam propagates on the road is consistent with the characteristic jam feature [J] of Sect. 2.4.1.
(ii) The flow rate q_{out}, density ρ_{min}, and average vehicle speed v_{max} in the outflow from the wide moving jam. These traffic variables are the characteristic parameters only under condition that free flow is formed in the jam outflow.
(iii) The mean vehicle density within the wide moving jam denoted by ρ_{max} that is also called the jam density.

[7] Note an GP is always a general case of a congested traffic pattern. This is because in three-phase traffic theory there are *only* the synchronized flow and wide moving jam phases in congested traffic and, in accordance with the GP definition, any GP consists of the both phases. This is independent of whether an GP appears at an on-ramp bottleneck or the GP is caused by a combination of several on- and off-ramps, etc.: An GP is a *generic* term for many *species*, i.e., subordinate terms of different types of GPs. Examples of these different GP types are an EGP, i.e., an expanded GP whose synchronized flow affects two or more effectual bottlenecks (see Sect. 7.3), a dissolving GP [36], and an GP with a non-regular pinch region (see Sect. 7.2.5).

Respectively, an SP in which congested traffic consists of synchronized flow *only* is the *generic* term for many different types of SPs. Examples of these different SP types are a moving SP, a localized SP, a widening SP (Sect. 7.2.1), and an ESP, i.e., an expanded SP whose synchronized flow affects two or more effectual bottlenecks.

This classification of congested patterns in three-phase traffic theory is made based on *common* empirical features of congested traffic (item 5 of Sect. 2.3) found during many years of observations of empirical congested patterns. Therefore, the classification of congested patterns into different types of GPs and SPs is well predictive and self-contained (Sect. 2.4.10 of [36]).

However, we should mention that the characteristic parameters can depend considerably on traffic parameters.

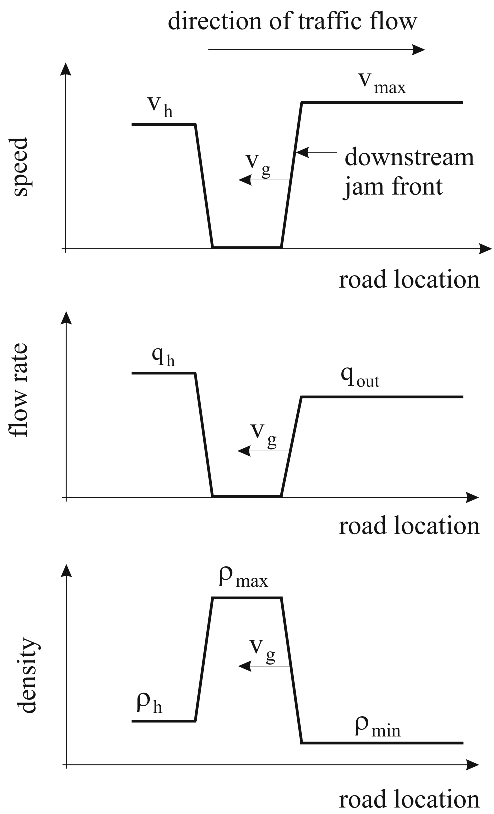

Fig. 2.10 Qualitative illustration of characteristic parameters of wide moving jam propagation [41]. Schematic representation of a wide moving jam at a fixed time instant. Spatial distributions of vehicle speed v, flow rate q, and vehicle density ρ in the wide moving jam, which propagates through a homogeneous state of initial free flow with speed v_h, flow rate q_h, and density ρ_h

The characteristic parameters of wide moving jam propagation are qualitatively illustrated in Fig. 2.10. In this figure, at a given time instant distributions of traffic variables along a road are shown associated with a wide moving jam propagating in an initial homogeneous free flow. The flow rate q_h and density ρ_h in this initial free flow are chosen to be greater, respectively, the average speed v_h to be lower than the related characteristic traffic variables of free flow formed in the jam outflow: $q_\mathrm{h} > q_\mathrm{out}$, $\rho_\mathrm{h} > \rho_\mathrm{min}$, $v_\mathrm{h} < v_\mathrm{max}$. Obviously, upstream of the jam the initial free flow occurs. However, this is not the case downstream of the jam. This is because during the jam propagation vehicles escaping from the jam at the downstream jam front form a new free flow with the flow rate q_{out}, density $\rho_{\min}$, and average speed $v_{\max}$.

2.5.1 Driver Time Delay in Acceleration and Mean Velocity of Downstream Jam Front

Concerning the mean velocity of the downstream front of a wide moving jam v_{g}, some general assumptions can be made [42]. Each driver within the jam can start to accelerate to either free flow or synchronized flow downstream after two conditions have been satisfied:

(i) The preceding vehicle has already begun to move away from the jam.
(ii) Due to the preceding vehicle motion, after some time the space gap between the two drivers has exceeded a space gap at which a safety condition for driver acceleration is satisfied:

- There is some time delay in vehicle acceleration at the downstream front of the wide moving jam.

The mean time in vehicle acceleration at the downstream front of a wide moving jam will be denoted by $\tau^{(\text{a})}_{\text{del, jam}}$. In empirical data,

$$\tau^{(\text{a})}_{\text{del, jam}} \approx 1.5 - 2 \text{ sec.} \tag{2.12}$$

The motion of the downstream front of a wide moving jam results from acceleration of drivers from the standstill within the jam to flow downstream of the jam. Because the average distance between vehicles inside the jam, including average length of each vehicle, equals $1/\rho_{\max}$, the velocity of the downstream front of the wide moving jam is

$$v_{\text{g}} = -\frac{1}{\rho_{\max}\tau^{(\text{a})}_{\text{del, jam}}}. \tag{2.13}$$

In empirical observations,

$$v_{\text{g}} \sim -15 \text{ km/h}. \tag{2.14}$$

2.5.2 The Line J

The characteristic parameters of wide moving jam propagation and the jam feature [J], which defines the wide moving jam phase in congested traffic (Sect. 2.4.1), can be presented by a line in the flow–density plane. This line firstly introduced in [41] and studied in [28–34, 40, 43] is called the "line *J*" (Figs. 2.11 and 2.12).

The slope of the line *J* is equal to the characteristic velocity v_g. If in the wide moving jam outflow free flow is formed, then the flow rate q_{out} in this jam outflow and the related density ρ_{min} give the left coordinates $(\rho_{min},\ q_{out})$ of the line *J*; as abovementioned, q_{out}, ρ_{min}, and the related average vehicle speed v_{max} are characteristic parameters of wide moving jam propagation (Fig. 2.10). The right coordinates $(\rho_{max},\ 0)$ of the line *J* are related to the traffic variables within the jam, the density ρ_{max} and flow rate $q_{min} = \rho_{max} v_{min}$, where the average vehicle speed within the jam v_{min} is here assumed to be zero that results in $q_{min} = 0$ within the jam (Fig. 2.11).

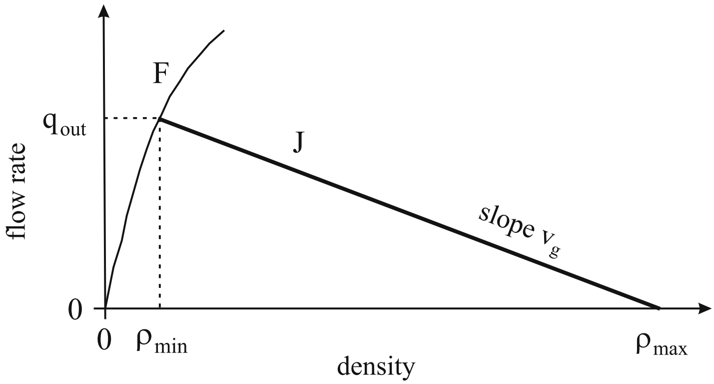

Fig. 2.11 Qualitative representation of the fundamental diagram of free flow (*F*) together with the line *J* (line *J*) whose slope is equal to the mean downstream jam front velocity v_g [41]

Because the slope of the line *J* is equal to the characteristic jam velocity v_g (2.13), on the line *J* the derivative

$$\frac{dq}{d\rho} = v_g, \tag{2.15}$$

i.e., in accordance with the line *J* definition it satisfies the equation

$$q(\rho) = \mid v_g \mid (\rho_{max} - \rho) \tag{2.16}$$

that using (2.13) can be rewritten in the equivalent form as

$$q(\rho) = \frac{1}{\tau^{(a)}_{\text{del, jam}}} \left(1 - \frac{\rho}{\rho_{max}}\right). \tag{2.17}$$

From Eq. (2.16), for the flow rate in free flow formed in the jam outflow we get the formula

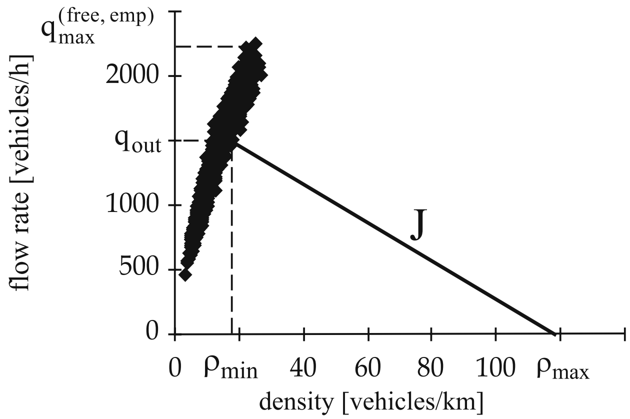

Fig. 2.12 Empirical example of the line *J*: Representation of the propagation of the downstream front of the downstream jam in the sequence of two wide moving jams in Fig. 2.8 by the line *J* in the flow–density plane and data for free flow (black diamonds). Taken from [40]

$$q_{out} = \mid v_g \mid (\rho_{max} - \rho_{min}), \tag{2.18}$$

which, as follows from (2.17), can also be written as

$$q_{out} = \frac{1}{\tau^{(a)}_{del,\ jam}} \left(1 - \frac{\rho_{min}}{\rho_{max}}\right). \tag{2.19}$$

A result of empirical observations of wide moving jam propagation is that the maximum flow rate in free flow $q_{max}^{(free,emp)}$ is considerably greater than the flow rate in free flow in the wide moving jam outflow q_{out} (Fig. 2.12) [40]:

$$q_{max}^{(free,\ emp)} > q_{out}. \tag{2.20}$$

In particular, for 1-min average measured traffic data has been found that [40]

$$\frac{q_{max}^{(free,\ emp)}}{q_{out}} \approx 1.5. \tag{2.21}$$

2.6 Microscopic Criterion for Traffic Phases in Congested Traffic

In this section, we show that when *microscopic* traffic variables are measured, then the distinguishing the synchronized flow and wide moving jam phases can be possible, even if the microscopic traffic variables are measured at only one road location within a congested pattern.

2.6.1 Traffic Flow Interruption within Wide Moving Jam

The spatiotemporal criteria for a wide moving jam [J], which distinguish the wide moving jam and synchronized flow phases, can be explained by a traffic flow interruption effect within a wide moving jam: traffic flow is interrupted within the wide moving jam. As a result, there is no influence of the inflow into the jam on the jam outflow [36]. A difference between the jam inflow and the jam outflow changes the jam width only. This *traffic flow interruption effect within a wide moving jam* (flow interruption for short) is a general effect for each wide moving jam.

In a hypothetical case, when all vehicles within a moving jam do not move, the criterion for the traffic flow interruption effect within the jam is [5, 39]

$$I = \frac{\tau_{\mathrm{J}}}{\tau^{(\mathrm{a})}_{\mathrm{del,\ jam}}} \gg 1, \tag{2.22}$$

where τ_{J} is the duration of a wide moving jam (jam duration for short), i.e., the time interval between the upstream and downstream jam fronts measured when the wide moving jam propagates through a given road location; I is approximately equal to the vehicle number stopped within the jam.

In real traffic, there can be low speed vehicle motion within a wide moving jam (see Sect. 2.6.4). Due to the existence of such a low speed vehicle motion within a wide moving jam instead of hypothetical criterion (2.22) the following *sufficient* criterion for flow interruption within the jam can be used [5, 39]

$$I_{\mathrm{s}} = \frac{\tau_{\mathrm{max}}}{\tau^{(\mathrm{a})}_{\mathrm{del,\ jam}}} \gg 1, \tag{2.23}$$

where τ_{max} is the maximum time headway between two vehicles following each other within the jam ($\tau_{\mathrm{max}} \leq \tau_{\mathrm{J}}$).

We define a flow interruption interval within wide moving jam as follows [5, 39].

- A flow interruption interval within a wide moving jam is a time interval τ_{max} for which condition (2.23) is satisfied.

The interruption of traffic flow within a moving jam can also be found in *empirical* single vehicle data. In an example shown in Fig. 2.13, the flow interruption effect occurs two times during upstream jam propagation through a road detector (these time intervals are labeled "flow interruption" in Fig. 2.13 (c)). The values τ_{max} for the first flow interruption intervals within the wide moving jam are equal to approximately 50 s in the left lane, 24 s in the middle line, and 80 s in the right line. In accordance with (2.12), these values τ_{max} satisfy criterion (2.23). This means that traffic flow is interrupted within the moving jam, i.e., this moving jam can be associated with the wide moving jam phase [5, 39].

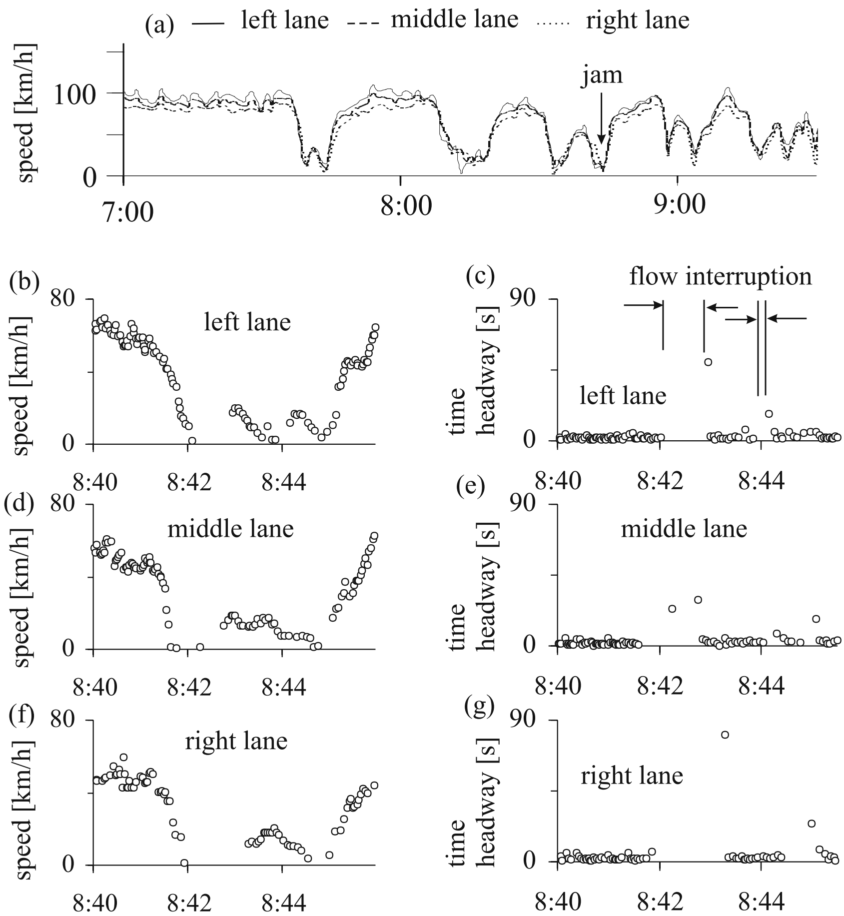

Fig. 2.13 Measured single vehicle data analysis: (a) Overview of measured data (1 min average data). (b–g) Single vehicle data for speed in three freeway lanes for a wide moving jam (left figures) labeled by “jam” in (a) and the related time headways (right figures). Taken from [5]

2.6.2 Flow Interruption Effect and Characteristic Jam Feature [J]

The flow interruption effect is a general effect for each wide moving jam [5, 39]:

- Condition (2.23) can be considered a microscopic criterion for the wide moving jam phase.

This microscopic criterion can be used to distinguish the synchronized flow and wide moving jam phases in single vehicle data. The microscopic criterion for the wide moving jam phase is possible to apply, even if traffic data is measured at a single road location.

This is because there is a deep connection between the flow interruption effect and characteristic feature [J] of wide moving jams: If there is a flow interruption interval within a moving traffic jam, then the jam exhibits the characteristic feature [J] to propagates though any bottleneck while maintaining the mean velocity of the downstream jam front, i.e., this jam is a wide moving jam.

To explain this, we note that during a long enough flow interruption interval τ_{max} in (2.23) there are at least several vehicles within a moving jam that are either in a standstill or they are moving with a negligible low speed in comparison with the speed in the jam inflow and outflow. Because τ_{max} is much longer than any driver time delays, at a given time instant there is a wide (in the longitudinal direction) enough road region associated with the flow interruption interval within which all vehicles can approximately be considered being in the standstill. We call this region within the jam as the flow interruption region. Thus a vehicle, which comes to a stop within the jam at the upstream boundary of the flow interruption region (this boundary coincides often with the upstream jam front), must wait for acceleration at least during the flow interruption interval τ_{max}: During this time interval other vehicles that are stopped downstream of the vehicle within the flow interruption region accelerate one after another from the standstill. This vehicle escaping from the standstill within the flow interruption region of the moving jam is independent of a traffic state in the jam outflow and it does not depend on whether there is a bottleneck or not[8].

This explains also why the downstream front of the wide moving jam propagates through the bottleneck while maintaining the mean velocity of the downstream jam front: this velocity v_g given by formula (2.13) is determined by the successive vehicle acceleration at the downstream front of the moving jam independent of traffic flow characteristics within the bottleneck. Thus under condition (2.23), the moving jam exhibits the characteristic jam feature [J], i.e., the jam is a wide moving jam.

2.6.3 Narrow Moving Jams

In an empirical example shown in Fig. 2.14, there are moving jams (Fig. 2.14 (b, c)). However, rather than wide moving jams these moving jams should be classified as narrow moving jams. In general, a narrow moving traffic jam is defined as follows.

- A narrow moving jam is a moving jam, which does not exhibit the characteristic feature [J] of a wide moving jam; for this reason, narrow moving jams belong to the synchronized flow traffic phase.

[8] A more detailed discussion of the link between the flow interruption effect and characteristic jam feature [J] can be found in Sect. 7.6.5 of the book [36].

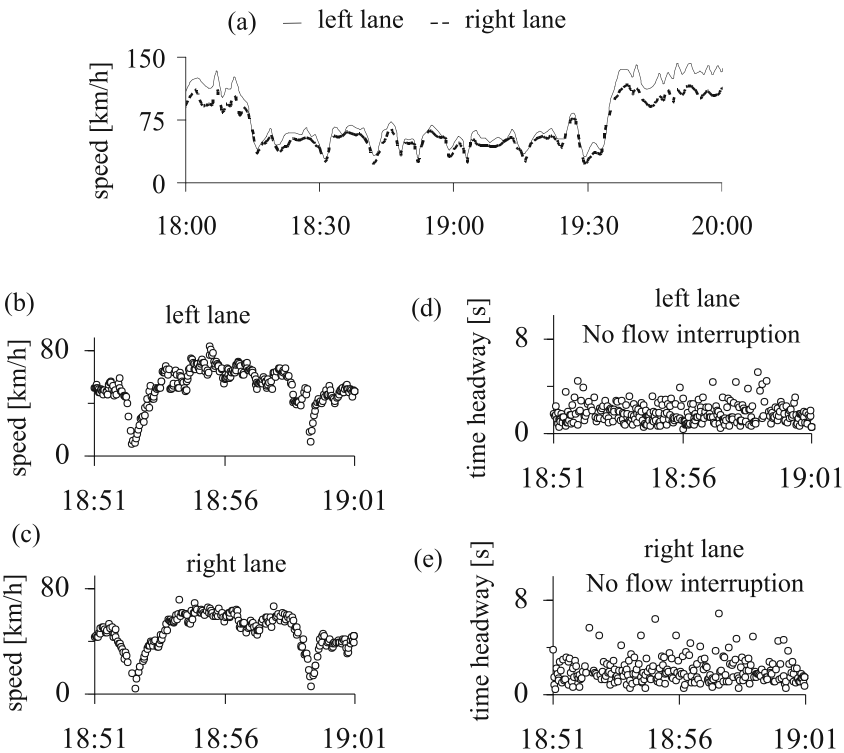

Fig. 2.14 Measured single vehicle data analysis of microscopic structure of narrow moving jams. (a) Overview of measured data (1 min average data). (b–e) Single vehicle data for speed in two freeway lanes for a sequence of narrow moving jams (left figures) and the related time headways (right figures). Taken from [5]

This is because there are no traffic flow interruption intervals within a narrow moving jam. Indeed, in empirical observations upstream and downstream of the jam, as well as within the jam there are many vehicles that traverse the induction loop detector. There is no considerable quantitative difference in time headways for different time intervals associated with these narrow moving jams and in traffic flow upstream or downstream of the jams (Fig. 2.14 (d, e)).

To understand this, we note that even if within a narrow moving jam the speed is equal to zero, then such narrow jam should consist of the jam fronts only: Each vehicle, which meets the narrow moving jam, can nevertheless accelerate later almost without any time delay within the jam. Within the upstream front vehicles must decelerate to a very low speed. However, the vehicles can accelerate almost immediately at the downstream jam front. These assumptions are confirmed by single vehicle data shown in Fig. 2.14 (b–e), in which time intervals between different measurements of time headways for different vehicles exhibit the same behavior outside of and within the jams. Even if within a narrow moving jam there are vehicles that are stopped, the condition

$$I_s = \frac{\tau_{max}}{\tau^{(a)}_{del,\ jam}} \sim 1 \qquad (2.24)$$

can be satisfied. Under this condition, there is no flow interruption interval within this jam. Thus independent of these narrow moving jams, traffic flow is not interrupted, i.e., the narrow moving jams are associated with the synchronized flow phase. This single vehicle analysis enables us to assume that congested traffic in Fig. 2.13 (b–g) is associated with a wide moving jam. In contrast, congested traffic in Fig. 2.14 (b–e) is associated with the synchronized flow phase.

In Sect. 2.6.2, we have shown a deep connection between the characteristic feature [J] and the existence of a flow interruption interval within a wide moving jam. Otherwise, if there is no flow interruption interval within a moving jam, i.e., rather than condition (2.23), the condition (2.24) is satisfied, as this is the case for a narrow moving jam, we can expect that the jam does not exhibit the characteristic feature [J]. This explains both the definition of the narrow moving jam and why the narrow moving jam belongs to the synchronized flow traffic phase.

In Fig. 2.15 (figures left), we support this qualitative explanation of narrow moving jams by numerical simulations in which a moving jam is artificially created in simulations downstream of an effectual on-ramp bottleneck. Before the jam due to its upstream propagation reaches the bottleneck, free flow is at the bottleneck. This means that before the moving jam under consideration reaches the bottleneck the jam is surrounded both downstream and upstream by free flows.

When the moving jam reaches the bottleneck, rather than the jam propagates through the bottleneck while maintaining the mean velocity of the downstream jam front, the jam causing traffic breakdown is caught at the bottleneck. In other words, the jam transforms into qualitatively another congested pattern whose downstream front is fixed at the bottleneck. Thus the characteristic feature [J] is not satisfied for the jam. We can conclude that this moving jam is a narrow moving jam, i.e., the jam belongs to the synchronized flow phase. The same conclusion can be made from a consideration of time headways within this moving jam presented in Fig. 2.15 (c, e) (figures left). We see that these time headways do not satisfy the microscopic criterion (2.23) for a wide moving jam: there is no traffic flow interval within this jam.

- A moving jam, within which there is no flow interruption interval, does not also exhibit the characteristic feature [J], i.e., such a moving jam is a narrow moving jam.

A qualitatively different case is presented in Fig. 2.15 (figures right). In this case, time headways within a moving jam satisfies the microscopic criterion (2.23) for a wide moving jam: there are traffic flow intervals within this jam both in the left and right road lanes. As expected, in the case the jam propagates through the bottleneck while maintaining the mean velocity of the downstream jam front (characteristic feature [J]), i.e., this jam is a wide moving jam.

The results of numerical simulations (Fig. 2.15) allow us to conclude that

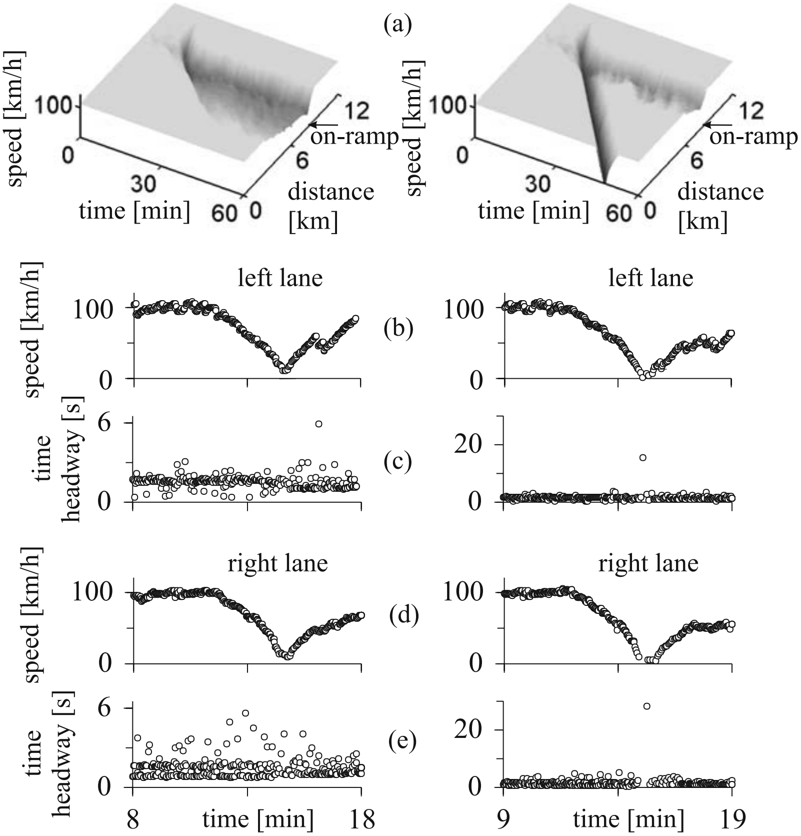

Fig. 2.15 Comparison of microscopic criterion (2.23) with macroscopic spatiotemporal objective criteria [J] and [S] for the phases in congested traffic of identical vehicles (results of model simulations). Left figures are related to a narrow moving jam. Right figures are related to a wide moving jam. (a) Vehicle speed on the main road in space and time that is averaged across two lanes. (b, d) Single vehicle data for speed in the left (b) and in right lanes (d). (c, e) Time headways associated with (b) and (d), respectively. Data in (b–e) is related to a road location 50 m downstream of the end of the on-ramp merging region. Taken from [39]

- the microscopic criterion (2.23) enables us indeed to distinguish the wide moving jam and synchronized flow phases in single vehicle data measured at one road location[9].

[9] It must be stressed that as we see from numerical simulations presented in Fig. 2.15, for an empirical proof of the microscopic criterion (2.23) for the traffic phases, we should compare results of phase identification based on this criterion in measured single vehicle data with the traffic phase definitions, i.e., with the macroscopic criteria for the traffic phases [J] and [S] (Sect. 2.4.1). However, such an empirical proof is possible, if the single vehicle data associated with a moving jam in the neighborhood of an effectual bottleneck is measured at many roads locations includ-

2.6.4 Moving Blanks within Wide Moving Jam

Between flow interruption intervals within the wide moving jam shown in Fig. 2.13 (b–g), vehicles within the jam exhibit time headways about 1.5–7 sec (Fig. 2.16). These time headways are considerably shorter than flow interruption intervals in Fig. 2.13 (c, e, g). The time headways are related to low speed states measured at detectors within the jam (Fig. 2.13 (b, d, f)).

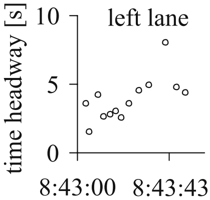

Fig. 2.16 Measured time headways associated with moving blanks in the left lane within a wide moving jam shown in Fig. 2.13 (b, c). Taken from [5]

To understand the effect of these low speed states, note that when vehicles meet the wide moving jam, firstly they decelerate usually to a standstill at the upstream jam front. As a result, the first flow interruption interval in all road lanes appears (Fig. 2.13 (c, e, g)). Space gaps between these vehicles can be very different and the mean space gap can exceed a safe space gap considerably, i.e., regions with no vehicles called as *blanks* can appear within the jam. A blank within the jam is defined as follows.

- A blank within a wide moving jam is a region with no vehicles.

Later vehicles move covering these blanks. This low speed vehicle motion is responsible for low speed states mentioned above (Fig. 2.13 (b, d, f)). Consequently, due to this low speed vehicle motion new blanks between vehicles occur upstream, i.e., the blanks move upstream within the jam. Then other vehicles within the jam that are upstream of these blanks begin also to move covering the latter blanks. This leads to moving blanks that propagate upstream within the jam.

We define a *moving blank* as follows [5, 36, 39].

- A moving blank within a wide moving jam is a region without vehicles, which moves upstream due to vehicle motion within the jam.

Thus we see that in a general case a microscopic structure of wide moving jam is as follows [5]:

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ing locations upstream and downstream of this bottleneck. In addition, before the jam reaches the bottleneck, free flow should be at the bottleneck. This is because only in this case we can prove whether the downstream front of the congested pattern exhibits the characteristic jam feature [J] or not. Unfortunately, we do not have such measured single vehicle data.

- A microscopic structure of wide moving jam consists of complex spatiotemporal alternations of flow interruption intervals and moving blanks.

2.7 Motivation for Traffic Phase Definitions

In some *averaged*, i.e., macroscopic traffic data of congested traffic, in particular which is measured outside of effectual bottlenecks, the traffic phase definitions [S] and [J] (Sect. 2.4.1) *cannot* be applied to perform an accurate identification of traffic phases. Thus a question arises:

- What is the sense of the traffic phase definitions [S] and [J], if the definitions cannot be used for the identification of traffic phases in some real macroscopic data of congested traffic?

A response on this question is as follows.

- Rather than to distinguish traffic phases in real measured macroscopic traffic data, the main *sense* of the phase definitions [S] and [J] is that the definitions result from and, therefore, distinguish qualitatively different *common* spatiotemporal characteristics of congested patterns (see item 4 of Sect. 2.3).
- These *common* spatiotemporal characteristics are associated with the behavior of the *downstream front* of a congested pattern at an effectual bottleneck at which traffic breakdown is possible: (i) If the pattern propagates through the bottleneck while maintaining the mean velocity of the downstream pattern front, then the congested pattern is a wide moving jam. (ii) In contrast with the wide moving jam, the downstream front of synchronized flow does not maintain the mean front velocity, in particular, the downstream front of synchronized flow is often fixed at the bottleneck.
- In turn, these common spatiotemporal characteristics of congested traffic patterns are the *origin* of hypotheses of three-phase traffic theory[10].
- This theory explains traffic breakdown and resulting congested traffic patterns in all known real measured traffic data [36].

Thus we can make the following conclusion about the motivation for the traffic phase definitions [S] and [J] made in three-phase traffic theory:

- The motivation for the traffic phase definitions [S] and [J] is the understanding of vehicular traffic congestion with the objective to derive new effective and reliable methods for traffic control and managements.

Additionally, the traffic phase definitions [S] and [J] are important for the validation of traffic flow models used for traffic control and dynamic traffic management.

The identification of the traffic phases in single vehicle data of congested traffic can be made with the microscopic criterion (2.23) for a wide moving jam. As

[10] Explanations of why the phase definitions [S] and [J] are the origin of hypotheses of three-phase traffic theory appear in Sect. 6.1.

explained in [5, 39], after downstream and upstream congested pattern fronts have been identified in averaged measured traffic data, this criterion can be used for the traffic phase identification, even if the single vehicle data is measured at one road location. Nevertheless, the identified traffic phases are valid only for the road location at which the single vehicle data is measured. The reason for this is as follows.

- A traffic phase that has just been identified with the microscopic criterion (2.23) at a road location can transform into another traffic phase at an adjacent road location outside of the location at which the single vehicle data is measured.
- Thus to perform an accurate traffic phase identification in congested traffic, single vehicle data measured simultaneously in space and time are needed.

Because the accurate traffic phase identification in congested traffic is important to overcome the problems of traffic control, single vehicle data measured simultaneously in time and space should be available in the future. This can be achieved through the use of new intelligent transportation systems, like car-to-car and car-to-infrastructure communication.

References

1. A.D. May, *Traffic Flow Fundamentals*, (Prentice-Hall, Inc., New Jersey, 1990)
2. *Highway Capacity Manual 2000*, (National Research Council, Transportation Research Board, Washington, D.C., 2000)
3. N.H. Gartner, C.J. Messer, A. Rathi (editors), *Traffic Flow Theory: A State-of-the-Art Report*, (Transportation Research Board, Washington DC, 2001)
4. Next Generation Simulation Programs, `http://ngsim.camsys.com/`
5. B.S. Kerner, S.L. Klenov, A. Hiller, H. Rehborn, Phys. Rev. E **73**, 046107 (2006)
6. B.S. Kerner, in *Encyclopedia of Complexity and System Science*, ed. by R.A. Meyers. (Springer, Berlin, 2009), pp. 9302–9355
7. I. Prigogine, R. Herman, *Kinetic Theory of Vehicular Traffic*, (American Elsevier, New York, 1971)
8. W. Leutzbach, *Introduction to the Theory of Traffic Flow*, (Springer, Berlin, 1988)
9. F.L. Hall, V.F. Hurdle, J.H. Banks, Transp. Res. Rec. **1365** 12–18 (1992)
10. M. Koshi, M. Iwasaki, I. Ohkura, in *Proc. 8th International Symposium on Transportation and Traffic Theory*, ed. by V.F. Hurdle. (University of Toronto Press, Toronto, Ontario, 1983), p. 403
11. L.C. Edie, R.S. Foote, Highway Res. Board Proc. Ann. Meeting **37**, 334–344 (1958)
12. L.C. Edie, R.S. Foote, in *Highway Research Board Proceedings*, (39. HRB, National Research Council, Washington, D.C., 1960), pp. 492–505
13. L.C. Edie, Oper. Res. **9**, 66–77 (1961)
14. L.C. Edie, P. Herman, T.N. Lam, Transp. Science **14**, 55–76 (1980)
15. J. Treiterer, J.A. Myers, in *Procs. 6th International Symposium on Transportation and Traffic Theory*, ed. by D.J. Buckley. (A.H. & AW Reed, London, 1974), pp. 13–38
16. J. Treiterer, *Investigation of Traffic Dynamics by Aerial Photogrammetry Techniques*, (Ohio State University Technical Report PB 246 094, Columbus, Ohio, 1975)
17. F.L. Hall, K. Agyemang-Duah, Trans. Res. Rec. **1320**, 91–98 (1991)
18. L. Elefteriadou, R.P. Roess, W.R. McShane, Transp. Res. Rec. **1484**, 80–89 (1995)
19. B.N. Persaud, S. Yagar, R. Brownlee, Trans. Res. Rec. **1634**, 64–69 (1998)
20. F.L. Hall, M.A. Gunter, Trans. Res. Rec. **1091** 1–9 (1986)

21. F.L. Hall, Trans. Res. A **21** 191–201 (1987)
22. H. Okamura, S. Watanabe, T. Watanabe, Trans. Res. Cir. **E-C018** (2000)
23. M. Lorenz, L. Elefteriadou, Trans. Res. Cir. **E-C018** 84–95 (2000)
24. H. Zurlinden, Ganzjahresanalyse des Verkehrsflusses auf Straßen. *Schriftenreihe des Lehrstuhls für Verkehrswesen der Ruhr-Universität Bochum*, Heft 26 (Ruhr-Universität Bochum, Bochum, 2003)
25. W. Brilon, J. Geistefeld, M. Regler, in *Transportation and Traffic Theory*, ed. by H.S. Mahmassani. Proceedings of the 16th Inter. Sym. on Transportation and Traffic Theory, (Elsevier, Amsterdam, 2005), pp. 125–144
26. W. Brilon, H. Zurlinden, Straßenverkehrstechnik, Heft 4, 164 (2004)
27. W. Brilon, M. Regler, J. Geistefeld, Straßenverkehrstechnik, Heft 3, 136 (2005)
28. B.S. Kerner, in *Proceedings of the* 3rd *Symposium on Highway Capacity and Level of Service*, ed. by R. Rysgaard. Vol 2 (Road Directorate, Ministry of Transport – Denmark, 1998), pp. 621–642
29. B.S. Kerner, Phys. Rev. Lett. **81**, 3797–3400 (1998)
30. B.S. Kerner, in *Traffic and Granular Flow' 97*, ed. by M. Schreckenberg, D.E. Wolf. (Springer, Singapore, 1998), pp. 239–267
31. B.S. Kerner, Trans. Res. Rec. **1678**, 160–167 (1999)
32. B.S. Kerner, in *Transportation and Traffic Theory*, ed. by A. Ceder. (Elsevier Science, Amsterdam 1999), pp. 147–171
33. B.S. Kerner, Physics World **12**, 25–30 (August 1999)
34. B.S. Kerner, J. Phys. A: Math. Gen. **33**, L221-L228 (2000); Networks and Spatial Economics, **1**, 35 (2001); in *Progress in Industrial Mathematics at ECMI 2000*, (Springer, Berlin, 2001), pp. 286–292; Mathematical and Computer Modelling, **35**, 481–508 (2002)
35. B.S. Kerner, Trans. Res. Rec. **1710**, 136 (2000)
36. B.S. Kerner, *The Physics of Traffic*, (Springer, Berlin, New York, 2004)
37. B.S. Kerner, Phys. Rev. E **65**, 046138 (2002)
38. B.S. Kerner, J. Phys. A: Math. Theor. **41**, 215101 (2008); 369801 (2008)
39. B.S. Kerner, S.L. Klenov, A. Hiller, J. Phys. A: Math. Gen. **39**, 2001–2020 (2006)
40. B.S. Kerner, H. Rehborn, Phys. Rev. E **53**, R1297–R1300 (1996); R4275–R4278 (1996); Phys. Rev. Lett. **79**, 4030–4033 (1997)
41. B.S. Kerner, P. Konhäuser, Phys. Rev. E **50**, 54–83 (1994)
42. B.S. Kerner, in *Transportation Systems 1997*, ed. by M. Papageorgiou, A. Pouliezos. (Elsevier Science Ltd., London, 1997), pp. 765–770
43. B.S. Kerner, S.L. Klenov, P. Konhäuser, Phys. Rev. E **56**, 4200–4216 (1997)

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