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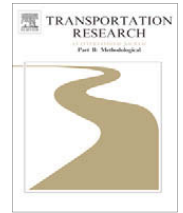
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## Criticism of three-phase traffic theory

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### ABSTRACT

After introducing the history and main points of three-phase traffic theory, we continue with a critical discussion based on its theoretical features and empirical traffic data. Our data originate from the German freeway A5 close to Frankfurt, i.e. from the same freeway section that has been the basis for the development of three-phase traffic theory. Despite of this, we end up with partially different interpretations of the observations. In particular, we highlight findings that are inconsistent with three-phase traffic theory and facts that question the concept of a “general pattern” of congested traffic flow. Finally, we discuss some open problems that call for the development of improved traffic models and further empirical studies.

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## 1. Introduction

Efficient transportation is one of the fundamental preconditions for a flourishing economics and a high quality of life. Nevertheless, the world witnesses an ever-growing level of congestion. Therefore, since the early days of computers, it has been tried to simulate and understand traffic flows. The on-going controversial debate about the right modeling approach, however, shows that traffic science has still not reached a generally accepted theoretical framework.<sup>1</sup>

Modeling attempts go back to the fifties of last century. It seems that Pipes (1953) came up with the first *microscopic* traffic model. Until today, similar car-following models have been intensively studied (Treiber et al., 2000, 2006; Kerner and Klennov, 2002). The first *macroscopic* traffic model based on the fluid-dynamic conservation equation dates back to the early days of traffic modeling as well (Lighthill and Whitham, 1955; Richards, 1956). It is still frequently used, and has been extended in many ways (Kühne, 1984; Kerner and Konhäuser, 1993; Hilliges et al., 1993; Daganzo, 1994; Treiber et al., 1999; Helbing, 2003). Some of these macroscopic models have been derived from *gas-kinetic* traffic models (Prigogine, 1961; Paveri-Fontana, 1975; Phillips, 1977; Hoogendoorn and Bovy, 1998; Helbing et al., 2001), others have been phenomenologically motivated.

The field of traffic modeling is now in a stage where researchers are trying to identify the best of all models. On the one hand, this is done by testing models against empirical data (Damrath and Rose, 2002; Brockfeld et al., 2003; Knospe et al., 2004; Nagel and Nelson, 2005; Schönhof and Helbing, 2007; Ossén and Hoogendoorn, 2005; NGSIM, 2006), on the other hand, criteria such as theoretical (in)consistency, simpleness, or robustness with respect to the choice of parameters are applied (Daganzo, 1995; Helbing, 2001). One of the most famous papers calling for theoretical consistency is the “Requiem for

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<sup>1</sup> Nevertheless, recent theoretical progress (Helbing, forthcoming) should be mentioned.

second-order fluid approximations of traffic flow” (Daganzo, 1995). It showed that the most common gas-kinetic and fluid-dynamic traffic models at that time had theoretical flaws.

In the meantime, this criticism could be overcome by improved models (Helbing, 1995, 1996; Treiber et al., 1999; Helbing, 2001, in print). Nevertheless, there are some surprising empirical observations that many traffic models do not reproduce. This has triggered many empirical analyses and new theoretical explanation approaches, including

- an extensive series of studies on empirical features of traffic flows (Kerner and Rehborn, 1996a,b, 1997; Kerner, 1998a,b, 2000b, 2002a,b; Kerner et al., 2006),
- a criticism of former traffic simulation models (Kerner, 2002a), especially all traffic models containing a fundamental diagram,
- the interpretation of empirical observations in terms of a three-phase traffic theory (Kerner and Rehborn, 1996b, 2002b, 2004), which has been repeatedly adjusted to new empirical findings, and
- the development of new, parameter-rich microscopic traffic models that fit the *interpretations* of three-phase traffic theory (Kerner and Klenov, 2002; Kerner et al., 2002; Kerner and Klenov, 2003).

These publications belong to the most influential and extensive bodies of work on traffic flows and have considerably stimulated their understanding and theoretical description.

In our opinion, this also applies to the macroscopic, Navier–Stokes-like traffic model (Kerner and Konhäuser, 1993) and its implications, although this model has been questioned and dropped during the development of three-phase traffic theory.

In Section 2, we will sketch the history and concept of three-phase traffic theory. As this theory has become quite complex over the years (Kerner, 2004), such a summary can certainly not be done without simplifications, i.e. we will have to restrict ourselves to the main points of this theory. Nevertheless, we will have to spend some time on its *evolution*, in particular as the theory has been adapted to new empirical findings over time. Some explanation approaches can only be understood, when problems with previous assumptions or interpretations are taken into account (see, for example, Section 3.1.3).

Section 3 will present theoretical inconsistencies and empirical results that question three-phase traffic theory as described in the book “The Physics of Traffic” (Kerner, 2004). Afterwards, in Section 4, we will X-ray the criticism of other traffic models in order to assess, whether and how it could be overcome. Finally, Section 5 presents our summary and conclusions, including a discussion of future challenges for the theoretical modeling and empirical analysis of traffic flows.

## 2. Historical development and main points of three-phase traffic theory

### 2.1. Modeling and simulation of jam formation before three-phase traffic theory

Many publications on traffic flows, including the very early ones, were driven by the desire to understand the fundamental diagram (i.e. the empirical relationship between traffic flow and density) and the breakdown of free traffic flow, particularly the emergence of traffic jams (see, e.g., Helbing (2001), for an overview). Particular attention has been paid to the process of jam formation in a Navier–Stokes-like traffic model (Kerner and Konhäuser, 1993). This second-order model, which is also known as the Kerner–Konhäuser model, is related to a similar model previously studied by Kühne (1984). A detailed investigation of the model was performed by computer simulations (Kerner and Konhäuser, 1994) and analytical calculations (Kerner et al., 1997). These computer-based and mathematical analyses were followed by a series of empirical studies, which started in 1996 (Kerner and Rehborn, 1996a,b, 1997; Kerner, 1998a).

The Kerner–Konhäuser model has a unique flow–density relationship in the stationary and homogeneous case. However, in a medium density range, traffic flow is unstable with respect to small perturbations due to a delayed adaptation of the vehicle speed to the respective local traffic situation. This can lead to the formation of “phantom traffic jams” (Kerner and Konhäuser, 1993, 1994). Vehicles in these *jams* have speeds close to zero and are densely packed. The jams themselves are travelling backwards, as vehicles are moving out at the front and joining at the end. While narrow jams tend to grow, the spatial extension of moving jams stabilizes in so-called “wide moving jams”, the spatial extension (low-velocity area) of which is significantly larger than the extension of their jam fronts. Wide moving jams are characterized by “characteristic constants” such as their negative, typical propagation speed  $c_0$  and their outflow  $Q_{\text{out}}$  (Kerner and Konhäuser, 1994; Kerner and Rehborn, 1996a). These constants are related to a self-organized, linear flow–density relationship, the “*jam line*” (Kerner and Rehborn, 1996a; Kerner et al., 1997). According to the authors, models of wide moving jams fit the related empirical observations well (Kerner, 2004, p. 80).

### 2.2. Empirical classification of traffic phases and fundamental hypothesis of three-phase traffic theory

Within the framework of three-phase traffic theory, the first traffic phase is given by “*free traffic*”, characterized by high vehicle speeds which may differ among neighboring lanes. This phase is defined by traffic flows with a monotonously increasing and almost linear flow–density relationship, while all traffic states showing points in the flow–density plane right of this line are classified as congested (cf. Kerner, 2004, p. 23).

Wide moving jams constitute the second traffic phase. The criteria for the presence of a wide moving jam are as follows (Kerner and Rehborn, 1996a; Kerner, 2004): while the vehicles in the jam have very low speeds, sometimes as low as zero,

the downstream jam front propagates upstream with a constant average velocity. This holds for a wide moving jam “even as it propagates through other (possible very complex) traffic states of freeway bottlenecks” (cf. Kerner, 2004, p. 27). The citation refers to later empirical results (Kerner, 2000b) concerning the interaction with another congested traffic phase that often occurs upstream of bottlenecks. This constitutes the third traffic phase, called “*synchronized flow*” with significant, non-zero vehicle speeds (Kerner and Rehborn, 1996b)—in contrast to wide moving jams (Kerner and Rehborn, 1996a). Synchronized flows denote all congested traffic states that cannot be classified as wide moving jam (cf. Kerner, 2004, p. 27): “In contrast to the ‘wide moving jam’ traffic phase, the downstream front of the ‘synchronized flow’ traffic phase does *not* maintain the mean velocity of the downstream front. In particular, the downstream front of synchronized flow is often *fixed* at a freeway bottleneck” (see also Kerner and Rehborn (1996b)).

The name “synchronized flow” was chosen since the speeds in neighboring freeway lanes showed a tendency of synchronization and the flow was finite, i.e. non-zero. (Note that “wide moving jams” are *also* characterized by speed synchronization among lanes, but their flow drops to zero.) It seems to be natural to imagine “synchronized flow” as queued traffic upstream of bottlenecks of the freeway such as on-ramps, lane closures, or gradients, but this interpretation is not fully in accordance with three-phase traffic theory, as it also states that the dynamics of the downstream congestion front may depend on details of the traffic pattern *upstream* of the bottleneck (Kerner, 2000b). “Synchronized flow” typically shows a wide scattering of flow–density data. Therefore, it completely differs from free flow and the jam line (the theoretically expected, self-organized flow–density relation for wide moving jams), and it establishes another traffic phase. When the phenomenon of “synchronized flow” was published for the first time (Kerner and Rehborn, 1996b), traffic models based on a unique flow–density relationship did not convincingly reproduce the wide scattering of “synchronized flow”. Within three-phase traffic theory, this discrepancy is seen as a substantial, even constitutive problem: the “fundamental hypothesis of three-phase traffic theory” postulates that each congested flow–density point in synchronized flow is *metastable*. This would imply the existence of a “multitude of steady states” covering a large area of the flow–density plane (Kerner, 1999).

### 2.3. Discussion

The “fundamental hypothesis of three-phase traffic theory” implies *by definition* that traffic models within the “fundamental diagram approach” (characterized by a one-dimensional and unique flow–density relationship in the stationary and homogeneous case) could, for *principal* reasons, not provide a satisfactory understanding of traffic phenomena. However, this hypothesis can *not* be tested. Due to the inherent wide scattering of synchronized flow, the hypothetical steady states can *not* be proven empirically (cf. Kerner, 2004, p. 97). Nevertheless, it is an integral part of three-phase traffic theory and has been the basis for the development of new traffic models (Kerner and Klenov, 2002; Kerner et al., 2002).

From our point of view, the empirical observations, in particular the widely scattered flow–density data, can also be reproduced by simpler traffic models (see Section 4.1). However, at the time when the concept of “synchronized flow” was elaborated, computer simulations of traffic flows were not advanced enough for this, due to the following reasons:

- First, many simulations of macroscopic traffic models were restricted to *periodic* boundary conditions (i.e. circular traffic). Although on- and off-ramps could be added to periodic systems (Kerner et al., 1995), people had various problems simulating *open* systems. For example, the propagation direction of perturbations changes, when traffic flow breaks down, which requires to switch between different kinds of boundary conditions (Helbing and Treiber, 1999).
- Second, most studies of macroscopic traffic models were carried out with single-class models (which did not consider the heterogeneity of driver–vehicle behaviors) and with effective single-lane models (which did not take into account the impact of lane changes). The synchronization of flows on neighboring lanes, however, is clearly a *multi-lane* effect involving lane changes (Shvetsov and Helbing, 1999).
- Third, the instability properties of the models were not sufficiently consistent with empirical data.
- Forth, the measurement process of empirical data was not properly reflected in the generation and evaluation of simulation results.

The resulting problems, when trying to reproduce empirical findings, triggered the development of “three-phase traffic theory”, while the computer simulation of traffic flows was advanced in parallel, providing alternative interpretations within the framework of models with a fundamental diagram (Helbing et al., 1999; Helbing and Treiber, 1999). Nevertheless, such models are still criticized to contradict observed traffic phenomena (Kerner, 2002a). Before we address these criticisms in Section 4, let us first discuss inconsistencies in the classification of congested traffic flows according to three-phase traffic theory and emphasize empirical phenomena that are not well incorporated in it.

## 3. Criticism of three-phase traffic theory

### 3.1. Conceptual problems

The distinction of the three different traffic phases is made in practice by the patented concept FOTO/ASDA (Kerner et al., 2004). While, theoretically, 3 rules should be sufficient to classify the 3 traffic phases, this concept uses 13 different quan-

titative criteria. From our point of view, this indicates already that more than 3 traffic phases are needed to appropriately reflect the complexity of traffic flow phenomena. In fact, as the following section will show, one must distinguish several subclasses and special cases.

### 3.1.1. Several different kinds of “synchronized flow”

In order to account for the empirical observations, “synchronized flow” has been subdivided into a variety of different kinds, which undermines the concept of summarizing all states as “synchronized flow” that are not classified as free traffic or wide moving jams.

For example, “synchronized flow” was subdivided into three different kinds, based on observations of one-minute averages measured at single cross-sections of the freeway (Kerner and Rehborn, 1996b):

1. “stationary and homogeneous states”, where both the average speed and the flow rate are stationary for a few minutes,
2. “homogeneous-in-speed states”, which look similar to the upper part of the free branch of the fundamental diagram (corresponding to a stationary average vehicle speed), but with a lower desired velocity (see also Kerner (1998b, 2004)),
3. “non-stationary and non-homogeneous states” (see also Kerner (1998b, 2004)).

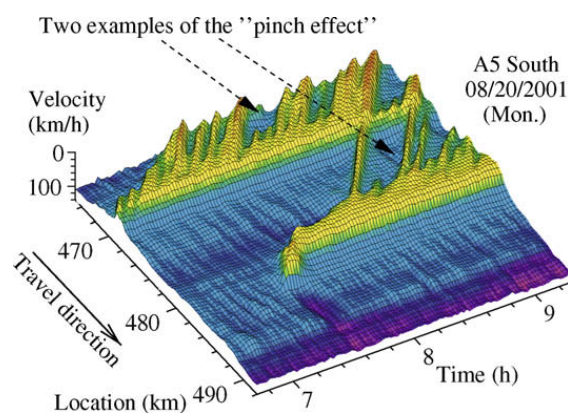
Furthermore, it was suggested that, upstream of a bottleneck, “synchronized flow” would breed wide moving jams based on a “pinch effect” (Kerner, 1998a): upstream of a section with “synchronized” congested traffic close to a bottleneck, a so-called “pinch region” would spontaneously give birth to narrow jams (vehicle clusters). These perturbations would be growing while travelling further upstream. Eventually, wide moving jams would be formed by the merging or disappearance of narrow jams. Once formed, wide jams would suppress the occurrence of new narrow jams in between. Instead of forming wide jams, however, narrow jams would be able to coexist, if their distance was larger than about 2.5 km (Kerner, 1998a).

### 3.1.2. Complications and inconsistencies with regard to the general pattern and the moving synchronized pattern

The congestion pattern related to the “pinch effect” is called “general pattern” (Kerner, 2002b). As the “general pattern” consists of a spatial sequence of differently appearing kinds of congested traffic flow, the chosen terminology masks that there may exist *more* than two congested traffic states. It also makes it difficult to decide when exactly a narrow jam born in the “general pattern” becomes a “wide moving jam”. Without a clear classification criterion, however, a distinction of the two different congestion phases (“wide moving jams” and “synchronized flow”) becomes questionable.

Three-phase traffic theory states that congestion patterns at isolated bottlenecks have the form of a “general pattern” (Kerner, 2002a). Therefore, they should more or less look like the one displayed in Fig. 1. But the term “general pattern” is also used for a large variety of congestion patterns of different appearance, e.g. “dissolving general patterns” (DGP), single moving jams, and “AGP” (an alternation of free traffic and “synchronized flow”) (Kerner, 2002a,b). We doubt that such an approach is useful for explaining the fundamentals and particularities of traffic flows.

Another congestion pattern that reveals serious classification problems is the “moving synchronized pattern” (MSP). “Moving synchronized patterns” look like wide moving jams, but they are not, as they stop propagating at a bottleneck and form a “localized synchronized pattern”. “Moving synchronized patterns” often travel with the same speed as “wide moving jams”, however, “... in contrast with a wide moving jam, if an MSP reaches a bottleneck, the MSP is caught at the bottleneck: the MSP that propagates upstream can exist only for a finite time” (Kerner, 2005, p. 187). Furthermore, it is explicitly stated that “moving jams, which are caught at the bottleneck, are related to the synchronized flow phase rather than to the wide moving



**Fig. 1.** Representative example of the “pinch effect”. The underlying data are from the German freeway A5 in direction South. The solid arrow in this graph indicates the driving direction of vehicles. Upstream of intersection Bad Homburg at kilometer 481 (see Fig. 2), one can clearly see the typical spatial sequence characterizing a “general pattern”, i.e. an area of relatively stationary and homogeneous “synchronized flow”, a “pinch region” in which perturbations (narrow jams) occur, and “wide moving jams”, travelling through another congestion pattern upstream of junction Friedberg at kilometer 471. Note that the average vehicle speed in this diagram is displayed downwards for better illustration of the congestion pattern (see Section 3.2.1). For a more detailed discussion of a similar figure see Schönhof and Helbing (2007).



jam phase” (Kerner, 2007, p. 29). That is, the actual type of traffic congestion indeed remains *undefined* until it reaches the next upstream bottleneck.

From our point of view, it is highly problematic to distinguish two identically looking states that cannot be told apart, if there is no upstream bottleneck. Even if there were a bottleneck allowing one to differentiate between a MSP and a wide moving jam, the “catching” of the jam and, thus, the identity of the traffic phenomenon would probably depend on the bottleneck strength, which leaves the classification dissatisfactory. Thus, a clear identification of a “wide moving jam” as opposed to “synchronized flow” is not possible, and three-phase traffic theory is severely questioned by this shortcoming. A proposal to circumvent the problem is presented at the end of the next subsection.

### 3.1.3. Jam generation at off-ramps

Three-phase traffic theory has particular problems explaining the observed transitions from free traffic to moving jams, without an intermediate transition to “synchronized flow”. In the course of time, various interpretations of such empirical findings have been suggested, but the formalization and critical testing of the proposed mechanisms is still not satisfactory:

1. On the one hand, the occurrence of wide moving jams at off-ramps is explained as follows (Kerner, 2000a, 2004): jams could only be generated in free traffic, if “synchronized flow” were suppressed by a suitable inhomogeneity of the freeway such as an off-ramp with a large amount of cars leaving the freeway. (It is argued that the critical amplitude of a density fluctuation required for the generation of jams would be much bigger than for a transition to “synchronized flow”.) This explanation, however, lacks consistency: despite the mentioned suppression of synchronized flow, “moving synchronized patterns” (that are caught at the next bottleneck, see Section 3.1.2) are often generated at off-ramps, too.
2. On the other hand, even single jams generated upstream of an off-ramp are interpreted as a very short form of the “general pattern” (Kerner, 2002b).
3. Finally, in some computer simulations, “wide moving jams” result from a “self-compression” of “synchronized flow” in a “moving synchronized pattern” (Kerner and Klenov, 2002). This suggests a further, alternative interpretation of how wide moving jams are generated at off-ramps.

In conclusion, there does not seem to be a consistent interpretation of transitions from free traffic to wide moving jams. From our point of view, the complexity of three-phase traffic theory would considerably decrease,

- if one would drop the differentiation of moving jams into “moving synchronized patterns” and “wide moving jams”, and
- if one would consider the possibility of transitions from moving jams to other congestion patterns.

## 3.2. Empirical observations not sufficiently accounted for

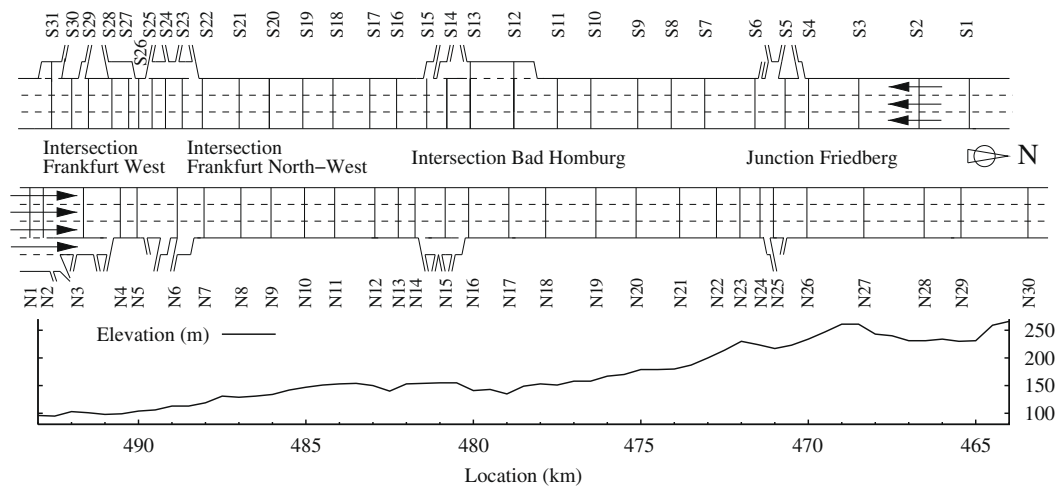
The empirical studies, on which three-phase traffic theory is based, have been mainly carried out for one freeway, namely the German freeway A5 close to Frankfurt, and certain intersections of this freeway. However, observations from other sites and rare or untypical observations have not been paid enough attention to, at least for a long time. This section will give several examples of such other observations, as they have important implications for the interpretation of congestion patterns and the development of a consistent traffic theory (Helbing, forthcoming).

### 3.2.1. Remarks on traffic data and analysis methods

Three-phase traffic theory is mainly based on the study of traffic on the German freeway A5 between 1996 and 2001 (see Fig. 2). As these data were not provided to us, we have requested traffic data for the same freeway stretch directly from the responsible traffic authorities and obtained extensive data sets for six months in 2001, cf. Schönhof and Helbing (2007). Although the time period is different, it is unlikely that the driver behavior or traffic dynamics has significantly changed on this freeway stretch. In fact, our empirical observations are largely consistent with the ones in the time period between 1996 and 2001, but some of our *interpretations* are different (see, for example, Section 3.2.2).

Our data analysis uses the “adaptive smoothing method” (Treiber and Helbing, 2002; Schönhof and Helbing, 2007), which was applied in all three-dimensional representations throughout this paper. It averages out fluctuations by means of a non-isotropic smoothing method, taking the propagation direction of perturbations into account. In free traffic, we set this speed to the truck velocity of 80 km/h, while in congested traffic, it was set to  $-16$  km/h, i.e. the dissolution speed of congested traffic. Note that, for better illustration, the average vehicle velocities as a function of space and time are displayed upside down in all three-dimensional diagrams of this paper, i.e. they increase in *downward* direction. This gives the velocity plots an appearance similar to density plots, but has the advantage that the velocity can be determined much more accurately by double loop detectors than the density. As a result, congested regions appear as “hills”, the size of which is indirectly related to delays in travel time.<sup>2</sup>

<sup>2</sup> A direct relation with travel time would be reached by displaying the inverse speed  $1/V$ . However, this quantity can diverge, as  $V$  can go to zero within traffic jams.



**Fig. 2.** Design of the German freeway A5 close to Frankfurt. Top: sketch of the investigated freeway section, showing the complexity of the German three-lane freeway A5 near Frankfurt/Main, with various gradients and multiple combinations of on- and off-ramps. Each measurement cross-section of the freeway is marked by a vertical line. It is named with the initial of the driving direction (“N” for North or “S” for South), followed by a number increasing in driving direction. The geographical position is given in kilometers according to the official notation of the road authorities. Bottom: height profile along the freeway. (After Schönhof and Helbing (2007).)

Note that the adaptive smoothing method allows one to distinguish small vehicle clusters from fluctuations. While fluctuations are averaged out, vehicle clusters cause perturbations that continue to exist while travelling forward, which makes it possible to identify them. In this way, one can, for example, see the fingerprints of long-lasting overtaking maneuvers of trucks, which cause growing vehicle platoons behind them (Helbing and Tilch, submitted for publication). This will be discussed in the next section.

3.2.2. The “boomerang effect” as alternative jam generating mechanism

The mechanisms generating wide moving jams and the laws governing transitions to other traffic states constitute key elements of three-phase traffic theory. According to the “pinch effect” (see Section 3.1.1), wide moving jams are born out of a pinch region with “synchronized flow”. A direct transition from free traffic to moving jams is questioned, while it is predicted for large enough perturbations and suitable flow conditions by the phase diagram of certain traffic models with a fundamental diagram (Helbing et al., 1999) (see Section 4.2). In the following, we will show that such transitions from free flow to moving jams do actually exist, and that some of them result from overcritical perturbations generated by the heterogeneity of traffic flows (the fact that cars and trucks are driving at different speeds).

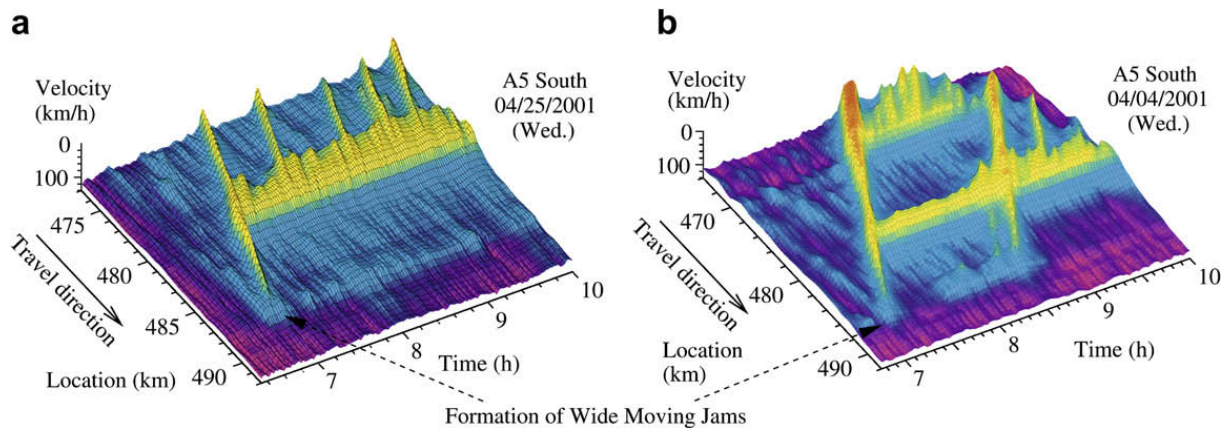
In our analysis of traffic data of the German freeway A5, 18 out of 245 congestion patterns were initiated by a “boomerang effect”. This effect also triggered “wide moving jams” several times (see Fig. 3). The “boomerang effect” is characterized by a small perturbation corresponding to a cluster of vehicles, which moves forward in downstream direction. In the course of time, this perturbation grows bigger. Eventually, it changes its propagation direction, which is reflected by the term “boomerang effect”. The upstream propagation sets in when the perturbation exceeds a certain amplitude (in terms of a drop in the vehicle speed). This backward motion can be understood as follows: while inside of a traffic jam vehicles are standing, vehicles are leaving it at its downstream front, but new vehicles are joining the jam at its upstream front. Altogether, this implies an upstream motion of the jam.

A closer investigation of the underlying data suggests that the “boomerang effect” relates to overtaking maneuvers of trucks. These cause “moving bottlenecks” (Gazis and Herman, 1992; Munoz and Daganzo, 2002) at a speed of about 80 km/h. The change in the propagation direction occurs slightly upstream of a freeway intersection, where obstructive interactions between the vehicle clusters and leaving vehicles occur. For an example of the triggering of congested traffic patterns by perturbations in free traffic flow see Fig. 4. The proper explanation of these observations requires<sup>3</sup>

1. to evaluate the truck fraction,
2. to consider overtaking maneuvers of trucks, and
3. to study the interaction of the resulting, growing vehicle platoon with a spatial inhomogeneity of the freeway (causing a growth of the perturbation amplitude and a “turning of the boomerang”).

These factors have *not* been sufficiently accounted for in previous empirical studies of traffic on the German freeway A5 close to Frankfurt and in the development of traffic theories based on these data. Therefore, alternative explanations have not been well enough considered.

<sup>3</sup> At least this holds, if cars and trucks have different speed limits, as on German freeways.



**Fig. 3.** Formation of wide moving jams. The spatio-temporal traffic patterns show the average velocity in downward direction for the sake of better illustration (see Section 3.2.1 for details). (a) Example of a wide moving jam triggered by a “boomerang effect” at kilometer 488 around 7am, without the previous existence of “synchronized flow”. The solid arrows indicate the driving direction. For details of the observed section of the German freeway A5 see Fig. 2. (b) Another example of a wide moving jam born by a “boomerang” effect occurring at the same location. As in (a), “synchronized flow” is triggered upstream of the intersection Bad Homburg at kilometer 481, when the wide moving jam passes the freeway intersection. In contrast to (a), no pinch effect is visible in (b) upstream of kilometer 481. According to three-phase traffic theory, however, there should be a transition from free traffic to “synchronized flow” and then to “wide moving jams”. For the further discussion of similar traffic patterns see Schönhof and Helbing (2007).

### 3.2.3. “General Patterns” are not general

While the term “general pattern” is used in a very flexible way, as it accounts for many differently appearing congestion patterns (see Section 3.1.2), there are still other traffic patterns, that are not well covered by the concept of the “general pattern”. Fig. 5 shows two examples. From this figure it is obvious that congestion patterns at flow-conserving bottlenecks look different from congestion patterns at freeway intersections (see Figs. 1 and 3a).

Fig. 5a shows an example of an oscillatory congested traffic pattern at an isolated and spatially confined bottleneck. It is caused by an accident a kilometer 478.325 at 9:50am. In comparison with the “general pattern” in Fig. 1, the formation of narrow jams starts *directly* upstream of the isolated bottleneck (the accident site), rather than *after* a region of stationary and homogeneous “synchronized flow”.<sup>4</sup> Moreover, the dissolution or merging of jams still continues seven kilometer upstream of the bottleneck. As the jams do not pass the intersection Friedberg at kilometer 471, one cannot classify the pronounced stop-and-go waves as “wide moving jams”. Hence, the characteristic spatial structure of a “general pattern” (“synchronized flow”, “pinch region” with jam formation, and a region of “wide moving jams”) cannot be seen here.

Fig. 5b shows that “wide moving jams” as well can be born at gradients without the previous transition to synchronized flow. Interpreting them as a “moving synchronized patterns”, which transform into “wide moving jams” by “self-compression” (Kerner and Klenov, 2002) would formally circumvent the problem. However, this is certainly not a satisfactory solution, as this would fundamentally question the definition and existence of a separate traffic phase of “wide moving jams”. A simpler interpretation would be based on the phase diagram (see Section 4.2), considering the instability of traffic flow in a certain density regime.

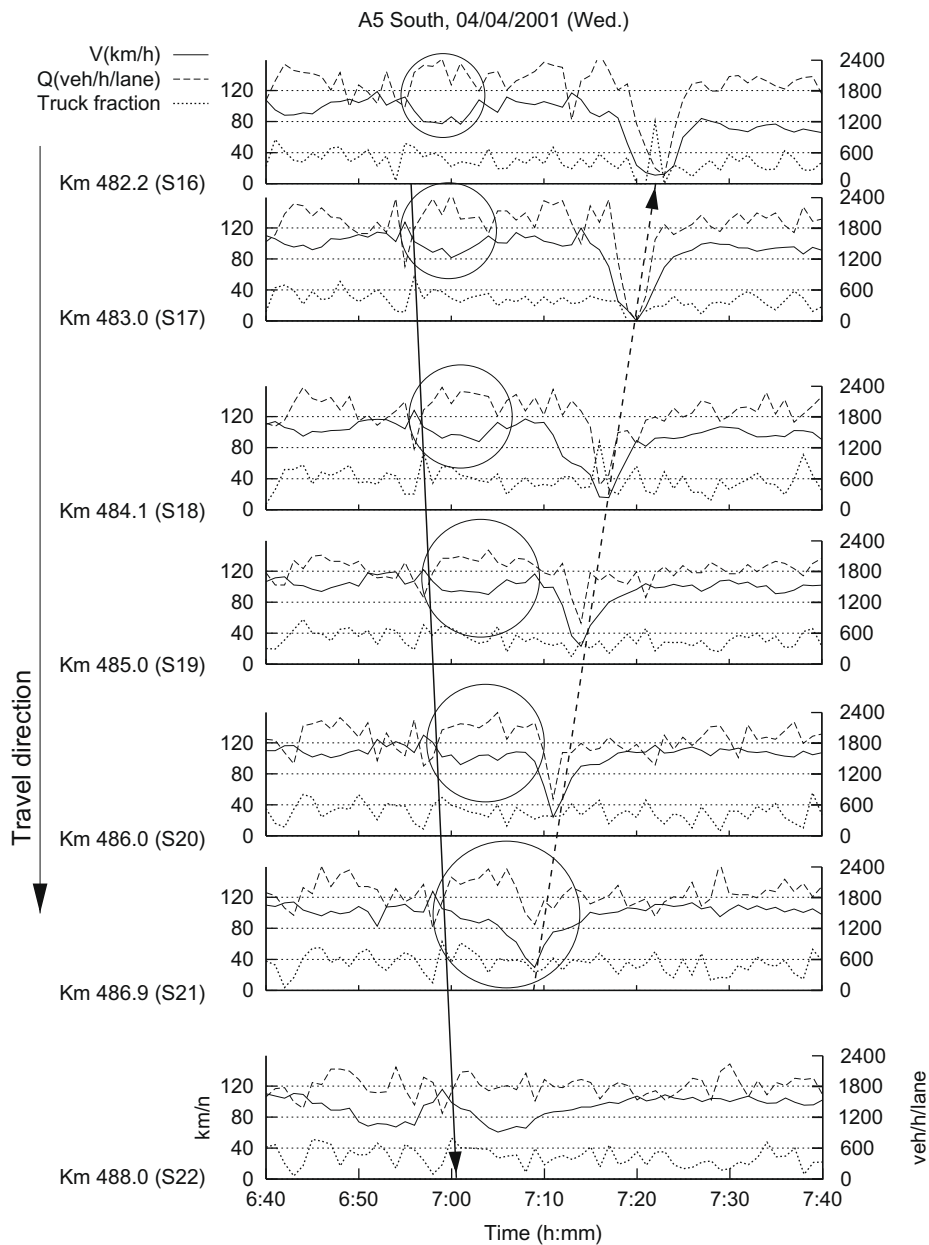
We suggest that, in contrast to the congestion patterns at isolated bottlenecks (see Fig. 5), “general patterns” are actually *specific* patterns resulting at freeway sections with an on-ramp *and* an off-ramp further upstream. Then, it is natural to interpret a “general pattern” as a combination of different kinds of congestion along the freeway (Schönhof and Helbing, 2007):

1. a spatially extended form of congested traffic between the on-ramp and the off-ramp, which may be considered as “synchronized flow”,
2. less serious congestion such as stop-and-go waves upstream of the off-ramp, where the bottleneck strength is reduced (as vehicles leaving the freeway free up some capacity), and
3. a special kind of congestion and dynamics in the vicinity of the off-ramp section (which relates to drivers who leave the freeway in response to congestion downstream of the off-ramp and, thereby, determine the particular features of the “pinch region”).

Certainly, we have to contradict the claim that “the effective bottleneck at (cross-section) D6 (here named S6, see Fig. 2) can indeed be considered as an isolated bottleneck at the on ramp” (Kerner, 2002b).

<sup>4</sup> A similar observation has been made at a factually isolated on-ramp, merging with an inner urban freeway next to the public observation tower in Kairo. The videos displayed at <http://www.trafficforum.org/stopandgo> were recorded under free flow conditions downstream of the on-ramp. Nevertheless, the on-ramp reproducibly triggered the breakdown of traffic flow and the emergence of upstream moving stop-and-go waves. Qualitatively very similar traffic patterns are generated by the microscopic traffic simulations available at <http://www.traffic-simulation.de/>.



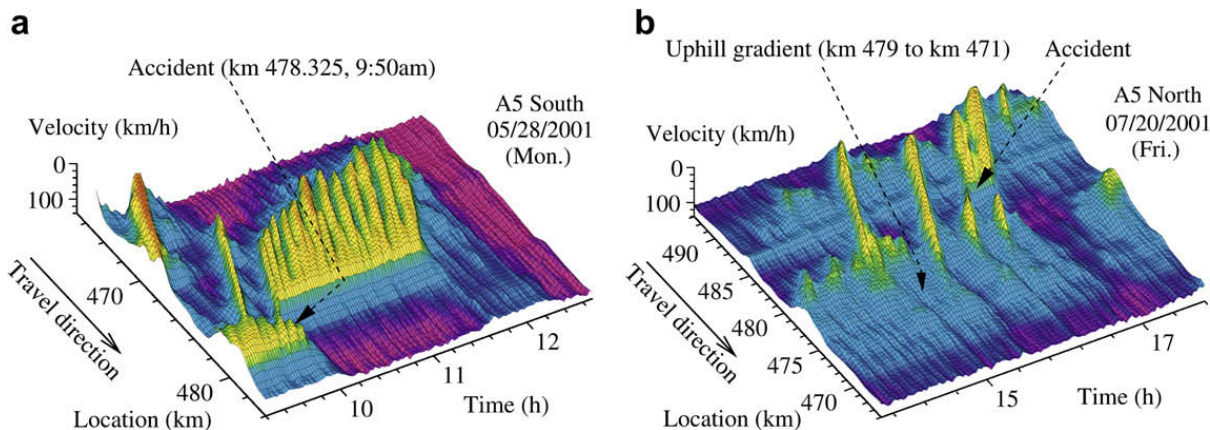


**Fig. 4.** Illustration of the “boomerang effect”. A detailed analysis of the traffic scenario in Fig. 3b shows that the “boomerang effect” starts with a peak in the truck fraction, which moves in travel direction at a velocity of about 75 km/h, see also Schönhof and Helbing (2007). The movement of the peak is illustrated by the solid arrow. After the peak, high flow values and a reduction in the average vehicle speed can be observed for some time period (see the part of the time series marked by the circles). This indicates a dense vehicle cluster queuing up behind overtaking trucks. While the cluster moves forward, its spatial extension grows: the time period, during which the vehicle velocity  $V$  is reduced, increases from one measurement cross-section to the next. Approximately one kilometer before the off-ramp at intersection Frankfurt North-West, which is characterized by many lane changing maneuvers due to a high off-ramp flow, the velocity drops to values around 60 km/h. This causes a traffic jam travelling *against* the driving direction (dashed arrow). The reduction in the average speed and flow now increases with time, thereby causing a growth in the *amplitude* of perturbation.

### 3.2.4. Existence of homogeneous congested traffic

According to three-phase traffic theory, the area of congested flow–density data is not further subdivided into areas of different stability. All feasible states are rather postulated to be metastable (Kerner, 1998b). In contrast to this, many traffic models predict the existence of areas of unstable, metastable and stable congested traffic flows (Helbing, 2001), see Section 4.2. Accordingly, there should be a stable traffic regime at high density, implying the existence of “homogeneous congested traffic” (Helbing et al., 1999). This, however, is incompatible with three-phase traffic theory.

Homogeneous congested traffic is defined as a form of congested traffic with a considerable spatial extension (typically larger than that of a wide moving jam), which may grow or shrink. The downstream front is usually located at a bottleneck. Vehicles in homogeneous congested traffic have a slow, but not necessarily zero speed. Applying some spatial and temporal smoothing, the average speed appears to be homogeneous, i.e. it is not of a pronounced oscillatory nature, in contrast, for example, to the “pinch effect”.



**Fig. 5.** Congestion patterns at isolated, flow-conserving bottlenecks. For related information see the design of the German freeway A5 close to Frankfurt depicted in Fig. 2, the video at <http://www.trafficforum.org/stopandgo>, and Schönhof and Helbing (2007). The driving direction is again indicated by solid arrows. (a) Moving jams triggered by an accident at kilometer 478.325 at 9:50am. (b) Wide moving jams appearing from 14:30 to 16:10 at the uphill gradient between kilometer 475 and kilometer 477 (see Fig. 2). The interruption of some jams at 16:20 is caused by an accident at kilometer 482.8. The “wide moving jams” disappear at intersection Frankfurt West due to several off-ramps, but before they pass the congested traffic upstream of the intersection Frankfurt North-West at kilometer 489. Note that the vehicle velocities in these diagrams increase in downward direction, see Section 3.2.1.

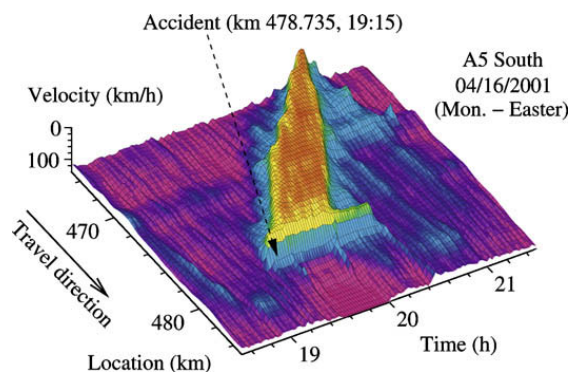
When studying empirical data, we did not observe any widely extended homogeneous congested traffic states upstream of freeway intersections. However, one would not expect to find them over there, as the freeway would otherwise be inappropriately dimensioned. In contrast, homogeneous congested traffic states were observed after serious accidents with lane closures (see Fig. 6). Such states require large bottleneck strengths exceeding about 700 vehicles per hour and lane (Schönhof and Helbing, 2007). That is, if cases of accidents are excluded from the data set, it is unlikely to find examples of homogeneous congested traffic.

We are aware that some inhomogeneity in the traffic flows results from the following effects: (i) random variations in the time gaps of vehicles (see Section 4.1), (ii) entering or leaving vehicles at freeway junctions or ramps, or related lane-changes upstream or downstream of them, (iii) difficulties in smoothly controlling the gas pedal at low speeds. However, the authors of this paper do not think that these effects of fluctuations and heterogeneities in driver–vehicle behavior would be fundamental properties of traffic flows that require a detailed theoretical description. For this reason, the adaptive smoothing method (ASM) has been used to separate noise effects from the systematic dynamics, using the same parameters for all congestion patterns. Hence, the difference between oscillating and homogeneous congested traffic is not a matter of differently chosen smoothing parameters, but it must be due to a different spatio-temporal dynamics.

#### 4. Revisiting the criticism of traffic models that are not based on three-phase traffic theory

##### 4.1. Wide scattering as effect of heterogeneous traffic

Three-phase traffic theory suggests that classical traffic models with a fundamental diagram would not be able to reproduce the wide scattering of congested flow–density data. This, however, mainly applies to models assuming identical driver–vehicle units. Already the consideration of two kinds of vehicles, cars and trucks, allows one to reproduce empirical flow–density diagrams semi-quantitatively, even with a simple macroscopic traffic model (Treiber and Helbing, 1999).



**Fig. 6.** Representative example of homogeneous congested traffic. The traffic pattern is caused by an accident with a blockage of freeway lanes, cf. Schönhof and Helbing (2007). The vehicle velocities in the diagram increase in downward direction for better illustration of the congestion pattern (cf. Section 3.2.1).

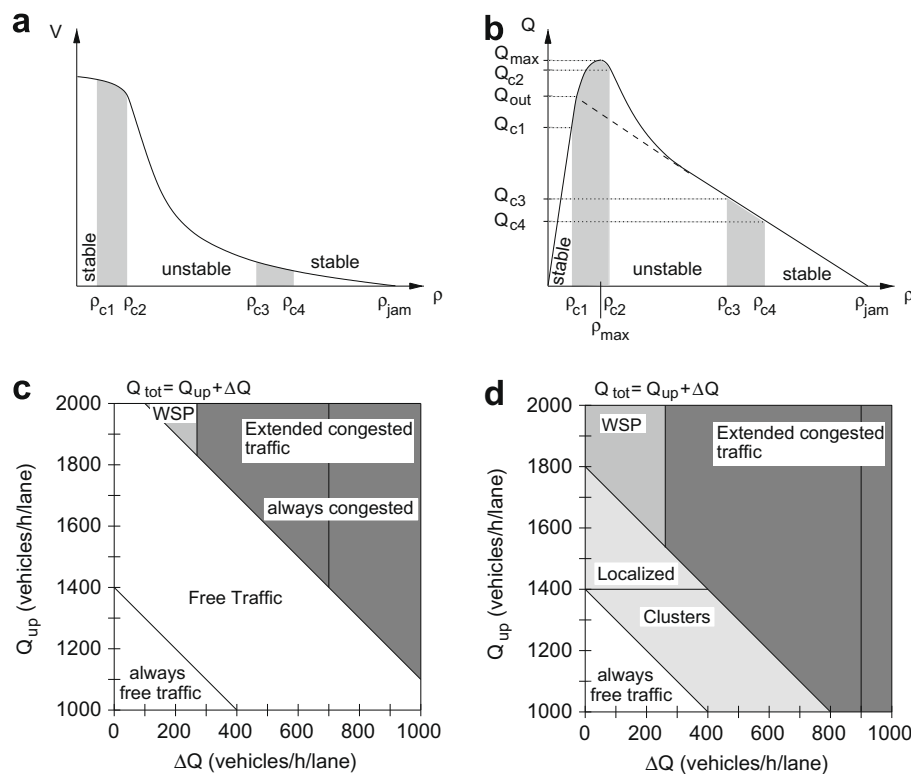
Moreover, empirical data are *quantitatively* compatible with the simple relationship

$$Q(\rho, T, \rho_{\max}) = \frac{1}{T} \left( 1 - \frac{\rho}{\rho_{\text{jam}}} \right) \quad (1)$$

for the flow  $Q$ , known as “jam line” (Kerner and Rehborn, 1996a), if not only the temporal variation of the density  $\rho$  is considered, but also the temporal variation of the average time gap  $T$  and the jam density  $\rho_{\text{jam}}$  (Nishinari et al., 2003). In such a case, the changes in the flow according to Eq. (1) have a surprisingly high correlation of more than 90% with the changes in the empirical flows. The scattering is mainly due to different behaviors of cars and trucks, with a large variation of the truck fraction. However, some amount of scattering also originates from inter-driver and intra-driver variability (Wagner et al., 1996; Hoogendoorn and Bovy, 1998), and from the aggregation by the measurement process (Treiber and Helbing, 2003).

Note that the time gaps are widely distributed with a heavy tail. Therefore, they average poorly with the time interval of data aggregation or sampling size (Nishinari et al., 2003). This implies a large temporal variation of the average time gaps  $T$ , which is of particular importance, as it leads to a varying slope  $-1/(\rho_{\text{jam}}T)$  of the jam line (Banks, 1999). Hence, variations in the average time gap  $T$  and the density  $\rho$  lead to movements in the flow–density-plane, which point into different directions, if traffic flow is congested. In free flow, however, variations of  $\rho$  and  $T$  lead to collinear movements. Altogether this explains both, the area of widely scattered flow–density data in the congested regime and the almost one-dimensional relationship for free traffic flow.

In summary, the wide scattering of congested flow–density data is not well compatible with models assuming *identical* vehicle behavior, but it is consistent with *multi-class* models assuming heterogeneous driver–vehicle units. This holds even for macroscopic multi-class models with a fundamental diagram for each vehicle class (Treiber and Helbing, 1999).



**Fig. 7.** Phase diagrams of flow-dependent traffic patterns and underlying instability diagrams for a model of freeway traffic with a fundamental diagram. The stable, linearly unstable, and metastable (grey) density areas are illustrated (a) in the velocity–density diagram and (b) in the flow–density diagram. While perturbations of any size are damped out in the stable areas and even small perturbations grow in the linearly unstable area, the outcome in the metastable regime (grey area) depends on whether the perturbation size is above or below a critical threshold (i.e. large perturbations grow, while small ones eventually disappear). The lower figures show a schematic representation of the idealized phase diagram of traffic states assuming (c) negligible and (d) large perturbations of the traffic flow. The diagrams are for an on-ramp flow merging into the freeway flow, but an application to other kinds of bottlenecks is possible as well (Treiber et al., 2000). The different areas indicate, for which combinations of the upstream freeway flow  $Q_{\text{up}}$  and the ramp flow  $\Delta Q$  certain traffic states can exist. The sum of both flows determines the total traffic demand  $Q_{\text{tot}}$ . According to our understanding, “extended congested traffic” can be classified as “synchronized flow”. Single “wide moving jams” triggered by large perturbations fall into the upper triangular subarea of “localized clusters”, while multiple “wide moving jams” emanating from “synchronized flow” (stop-and-go waves) belong to the upper left area of extended congested traffic and do not require large perturbations. Both areas of congested traffic states can be further subdivided, see Schönhof and Helbing (2007). Note the phase of “widening synchronized patterns” (WSP) in (c) and (d) (Kerner and Klenov, 2002), which also comprises “widening moving clusters”, here. It was found in recent computer simulations (Treiber et al., submitted for publication; Helbing et al., submitted for publication), and was missing in previous versions of the phase diagram. This phase exists if the critical density  $\rho_{c2}$  is greater than the density  $\rho_{\text{max}}$  belonging to the maximum flow (Helbing et al., submitted for publication), while  $\rho_{c2} \leq \rho_{\text{max}}$  was assumed in previous publications (Helbing et al., 1999).

#### 4.2. The phase diagram of traffic models with a “fundamental diagram” and its misinterpretation

The phase diagram of traffic states is a general concept, which makes quantitative predictions: it offers a systematic categorization of the variety of congested traffic states and provides an explanation for them (Helbing et al., 1999). In addition, for models with a fundamental diagram (characterized by a one-dimensional and unique flow–density relationship in the stationary and homogeneous case), it allows one to derive conditions for the possible existence of these states, based on the instability regimes of traffic flows and the self-organized, characteristic outflow from congested traffic (Helbing et al., 1999, submitted for publication).

The concept of the phase diagram also helps to categorize microscopic (Kerner and Klenov, 2003) and macroscopic traffic models (Lee et al., 1999) into different classes, depending on the number and kinds of congested traffic states they imply (Helbing, 2001; Helbing et al., submitted for publication). From our point of view, the phase diagrams of models based on three-phase traffic theory (Kerner and Klenov, 2003) differ from the original one found for the gas-kinetic-based traffic model (Helbing et al., 1999) mainly by the existence of an additional area, in which so-called “widening synchronized patterns” occur, and beyond this in the use of terminology: when identifying extended congested traffic flow with “synchronized flow” and moving localized clusters with moving synchronized patterns, the result is a high degree of qualitative similarity (Treiber et al., submitted for publication).

An idealized phase diagram of the intelligent driver model for a particular choice of parameters (Helbing et al., submitted for publication) is presented in Fig. 7c and d. Given suitable instability properties, the corresponding phase diagram is well consistent with empirical observations (Schönhof and Helbing, 2007; Helbing et al., submitted for publication). It also contains an area, where “widening synchronized patterns” can appear (Helbing et al., submitted for publication).

Due to the metastability of traffic flows, one needs to distinguish between a phase diagram for *small* perturbations in the traffic flow (see Fig. 7c) and one for *large* perturbations (see Fig. 7d). Apart from the area of WSP states, in which so-called widening synchronized patterns can occur, the latter corresponds essentially to the one presented in the original publication (Helbing et al., 1999). This distinction of perturbation sizes is important from a theoretical point of view, when transitions between different traffic states are discussed. However, as the perturbation size is empirically hard to determine, it is advised to compare empirical observations with a *superposition* of the two phase diagrams Fig. 7c and d.

The first proposed phase diagram (Helbing et al., 1999), which corresponds to Fig. 7d, but without the WSP area, and the underlying “fundamental diagram approach” have been criticized to contradict basic empirical observations for the following reasons (Kerner, 2002a):

1. Homogeneous congested traffic would not exist for large bottleneck strengths.
2. When the total traffic demand is increased, a transition from free traffic to moving jams should occur *before* the transition to extended forms of congested traffic, while most moving jams have been observed *after* a previous transition to “synchronized flow”.
3. When the total traffic demand goes down, the transition from extended congested traffic to free traffic would require the intermediate occurrence of a localized cluster, which is normally not observed.

In Section 3.2.4, it has been already shown that the first criticism is wrong.

The second and third claim are based on the phase diagram for *large* perturbations, which is depicted in Fig. 7d. Note, however, that the phase diagram looks different for small perturbations (see Fig. 7c). According to it, a *direct* transition from free flow to an extended form of congested traffic is expected, as soon as the total traffic volume  $Q_{\text{up}} + \Delta Q$  exceeds a certain threshold. That is, direct transitions from free traffic to “synchronized flow” should actually be *common*, in agreement with observations. While transitions to multiple moving jams are possible for *small* perturbations (Schönhof and Helbing, 2007), transitions to localized clusters (e.g. to single moving jams) require *large* perturbations (see Fig. 7c and d). Note that this holds for single, isolated bottlenecks, while congestion patterns reminding of localized clusters can *also* occur between on-ramps and upstream off-ramps (Schönhof and Helbing, 2007).

Furthermore, during the transition from extended congested traffic to free traffic, an intermediate localized cluster state will normally *not* occur. This is, because the total traffic demand has usually moved into the region of free traffic already *before* the extended congested traffic has melted down to the size of a localized cluster.

In conclusion, the above criticisms of phase diagrams for traffic models with a fundamental diagram are based on misunderstandings. The phase diagram is, in fact, very well consistent with empirical observations (Schönhof and Helbing, 2007; Helbing et al., submitted for publication).

## 5. Summary and outlook

In this paper, we have questioned three-phase traffic theory based on empirical data from the German freeway A5 close to Frankfurt. Most of the observations, which triggered the development of three-phase traffic theory, stem from this freeway stretch. While we have a high opinion of many fundamental discoveries within the context of three-phase traffic theory, we do not agree with a number of interpretations that went along with these discoveries, as will be summarized in the following:



1. Particularly with respect to the “moving synchronized pattern”, but also with respect to the transition from “synchronized flow” to “wide moving jams” in the “general pattern”, the classification of traffic states in three-phase traffic theory is not well defined and remains qualitative, i.e. mostly non-predictive.
2. The “general pattern” is most likely a consequence of the combination of one or several on-ramps with one or several off-ramps further upstream, i.e. a result of a particular freeway design. Congestion patterns at flow-conserving bottlenecks have a different appearance.

### 5.1. Methodological concerns

We see the source of our disagreement with several interpretations of three-phase traffic theory in some methodological shortcomings of previous empirical studies:

- The impact of accident-induced bottlenecks on the kind of congestion has not been sufficiently discussed. In fact, within half a year, there were about 500 accidents or breakdowns of vehicles on the freeway stretch investigated by us. While most of them had a minor impact on the traffic dynamics, some accidents caused major lane blockages. Together with a high traffic volume, such blockages were the precondition for the observation of homogeneous congested traffic states, which should not exist according to three-phase traffic theory.
- The impact of gradients (see Fig. 2), which can constitute flow-conserving bottlenecks, has been neglected. At such bottlenecks, we have observed congested traffic patterns that look different from “general patterns” (Schönhof and Helbing, 2007). In fact, they often show direct transitions from free traffic to moving jams.
- Complex multi-ramp setups (see Fig. 2) have been generalized to arbitrary bottleneck situations and compared with models for simple on-ramp scenarios. As these models were not developed for such scenarios, they could not reproduce “general patterns” well, but those can be easily be understood as effect of the particular freeway design (see Section 3.2.3).
- The influence of the truck fraction has not been accounted for. It is actually one important factor for the wide scattering of flow–density data in the congested traffic regime (Treiber and Helbing, 1999). Moreover, overtaking maneuvers of trucks seem to be responsible for the boomerang effect, which can trigger direct transitions from free traffic to moving jams (see Section 3.2.2).
- The relevance of the perturbation size for the transition from free traffic to particular kinds of congested traffic has not been properly taken into account (see Section 3.2.2). This has important implications for the comparison between traffic theories and empirical data (see Section 4.2), in particular with respect to the expected transitions between different traffic states.
- Empirical cross-sectional, time-averaged measurements for multi-class and multi-lane traffic have been compared with effective one-lane models for identical vehicles and without consideration of the measurement method. The resulting deviation between empirical and simulation results was interpreted as failure of models assuming a fundamental diagram of traffic flows. However, if the heterogeneity of traffic flows is adequately taken into account, observations like the wide scattering of congested flow–density data can, in fact, be well reproduced by simulation models (Treiber and Helbing, 1999).
- The impact of the adaptive speed control system along the studied freeway has not been discussed. This control system could, for example, be responsible for the existence of spatially extended “homogeneous-in-speed states” (cf. Kerner, 2004, pp. 298 and 356): these tend to occur when the overall flow in the three freeway lanes reaches stable values around 6000 vehicles per hour. Note that, in Germany, intelligent speed control systems usually display a speed limit of 80 km/h, when a value of 5400 vehicles per hour is exceeded (MARZ, 1999).
- The influence of the weather conditions on the vehicle flows, in particular the outflow from congested traffic, has not been sufficiently studied. According to recent empirical results, however, the variability of the outflow  $Q_{\text{out}}$  from congested traffic can at least partially be explained by the weather conditions (Schönhof, in press; Helbing et al., submitted for publication). Taking this variability into account, one finds a good agreement between theoretical and empirical phase diagrams (Schönhof and Helbing, 2007; Helbing et al., submitted for publication).

Considering the mentioned shortcomings, we conclude that some of the interpretations of three-phase traffic theory could be replaced by simpler interpretations (Helbing, forthcoming), as elaborated above. Nevertheless, there are attempts to reproduce the *interpretations* of three-phase traffic theory by parameter-rich microsimulation models, namely a continuous microscopic model (Kerner and Klenov, 2002, 2003) and a stochastic cellular automaton (Kerner et al., 2002). These models explicitly *implement* the hypothesis regarding the existence of metastable stationary and homogeneous “synchronized flows” in a wide area of the flow–density diagram. Since the simulated congestion patterns were named after the empirical ones, statements about *simulated* congestion patterns are now hard to distinguish from *empirically based* statements. Therefore, it is not always clear, which conclusions follow from models and which ones from empirical data.

### 5.2. Challenges for traffic modeling

In our opinion, it causes theoretical problems to separate “wide moving jams” from “moving synchronized patterns” as defined by three-phase traffic theory. We propose to consider them both as moving jams or “moving localized clusters”. One

would then have to accept that the “characteristic constants” are actually only constants for “wide moving jams”, i.e. in a limiting case or, in other words, under idealized conditions. Generally, the propagation speed and other characteristic constants of “wide moving jams” could vary for moving localized clusters. Such an approach would remove some of the theoretical inconsistencies of three-phase traffic theory.

However, our empirical observations do not only challenge *three-phase* traffic theory, but also *other* theories. For example, it needs to be checked whether current multi-class simulation models reproduce the empirical features of the “boomerang effect”, i.e.

- the growth of the spatial *extension* (width) of small perturbations, while they are travelling forward,
- the turning of the propagation direction slightly upstream of the off-ramp of a freeway intersection, and
- the subsequent growth of the perturbation *amplitude*.

Furthermore, while the original phase diagram approach (Helbing et al., 1999; Helbing et al., submitted for publication) provides a promising alternative to three-phase traffic theory, in order to reach a *quantitative* agreement with empirical findings, the upstream flows and ramp flows must be scaled by the respective outflow  $Q_{\text{out}}$  from congested traffic (Schönhof and Helbing, 2007). In contrast to many traffic models, the empirical outflows are varying considerably from day to day (Kerner, 2000b; Schönhof and Helbing, 2007), but this does not seem to be a sheer consequence of the varying truck fraction. The variation is also not just an effect of the statistical variation of congested flow–density data, as there is a *systematic* correlation of the outflow with the average vehicle speed in the congested area, and with the on- and off-ramp flows (Schönhof and Helbing, 2007). We believe that this calls for suitable microscopic multi-class traffic models considering the lane and route choice of driver–vehicle units. Moreover, the desired speed (or speed limit) is expected to have a systematic influence on the value of the outflow (Helbing et al., 2007). Therefore, the weather conditions should influence the outflow as well, which has recently been confirmed by empirical data (Schönhof, in press; Helbing et al., submitted for publication).

### 5.3. The need of further empirical studies

Until today, there is not only a lack of sufficiently detailed models of the traffic dynamics at freeway intersections. There is also a need of more detailed empirical data. In order to finally decide which traffic model provides the best description and what is the true cause of the spatio-temporal organization of the “general pattern”, it is necessary to have spatio-temporal data of single vehicles and their lane-changing behavior. Such data require to determine trajectory data along freeway intersections by means of special, video-equipped helicopters. While studies of this kind are expensive and technologically demanding, they will be needed to shed more light on the oldest and most central question of traffic theory, namely what are the real mechanisms and quantitative properties of traffic breakdowns.

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