The physics of traffic

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You're cruising along the motorway in top gear when, for no apparent reason, you slowly grind to a halt. Why do traffic jams form?

The physics of traffic

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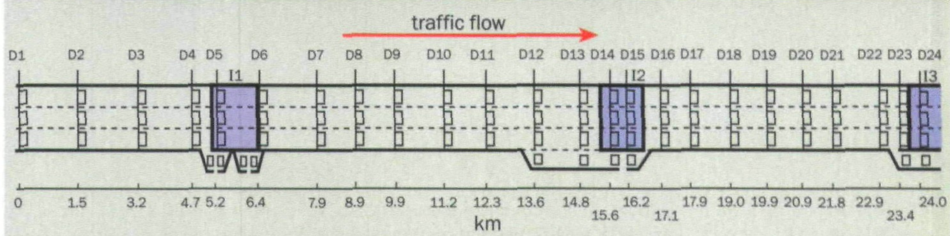
TRAFFIC jams are a fact of life for many car drivers. Every morning millions of drivers around the world sit motionless in their vehicles for long periods of time as they try to get to work, and then repeat the experience on their journeys home in the evening. The same thing often happens when they are driving to the coast for the weekend or to the airport to go on their holidays. They blame other drivers, increasing volumes of traffic and, inevitably, roadworks. So what has any of this got to do with physics?

1 Traffic watch



A schematic diagram of a 24 km section of the A5-South highway in Germany that includes intersections with three other highways (blue regions). The traffic flows from left (upstream) to right (downstream). The highway has three lanes, with the left-hand (top) lane being used for overtaking. There is a fourth lane for leaving and joining the highway at the three intersections. A series of detectors (D1, ..., D24) measures the velocity of every vehicle at 24 points on each lane, and a computer calculates the flow rate and the average vehicle speed in one-minute intervals.

Well, consider every car as an "elementary particle" that is constrained to move along a one-dimensional trajectory. This particle must also obey certain conditions: for example it must try to get from A to B and it must not collide with other particles! Could the collective behaviour of this complex system be responsible for traffic jams and the various other features associated with traffic flow? Does this behaviour have anything in common with the phenomena of self-organization and pattern formation that have been discovered in recent years? Indeed, should traffic phenomena be considered as part of statistical or nonlinear physics?

Over the past 50 years scientists have developed a wide range of different mathematical models of traffic flow to answer these questions. Clearly these models must be based on the real behaviour of drivers, and their solutions should show phenomena observed in real traffic. In the mid-1990s a new phase of traffic flow called synchronized traffic flow was discovered by the author and co-workers at Daimler-Benz (now DaimlerChrysler) in Stuttgart, Germany. This experimental discovery is having a major impact on the development of the various theoretical models that are used to predict the properties of traffic flow. These models are widely used by car makers and government traffic planners. DaimlerChrysler, for example, is using this research to develop new route guidance systems for individual vehicles and to optimize traffic flow over road networks.

Models

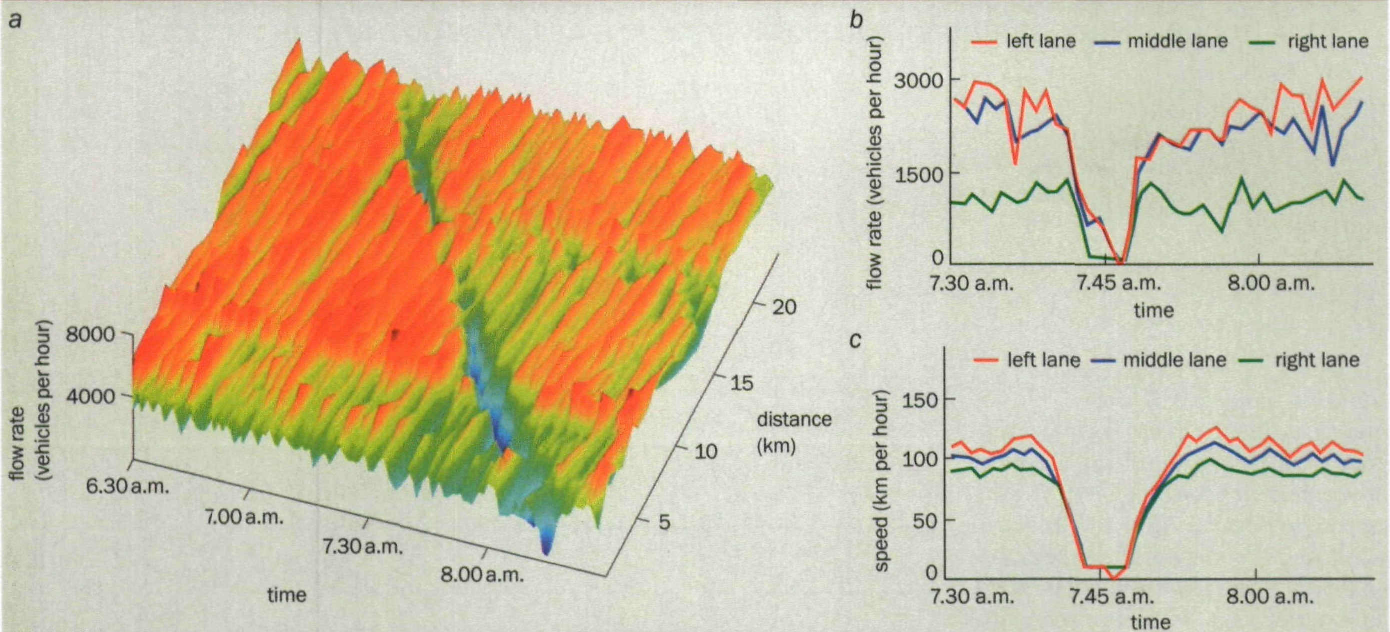
The first models of traffic flow were based on the collective properties of traffic such as the conservation of the number of vehicles, the balance of average vehicle speed and other, more complex, macroscopic properties of the flow. The first macroscopic models were proposed in 1955 by the late Sir James Lighthill and Gerald Beresford Whitham at Manchester University in the UK, and later in 1959 by Ilya Prigogine of the Free University of Brussels.

There have also been a huge number of microscopic models in which the individual behaviour of each vehicle is taken into account. Examples include the "car-following" approach of Robert Herman, Elliott Montroll and others at the research laboratories of General Motors in Warren, Michigan developed in the 1950s. In this approach a formula connects the acceleration of a car with the distance between it and the car ahead of it, and the relative velocity of the two cars. In the "optimal velocity" model developed by Masako Bando of Aichi University and colleagues in Japan in 1995, each driver tries to achieve an optimal velocity that depends on the distance to the car ahead.

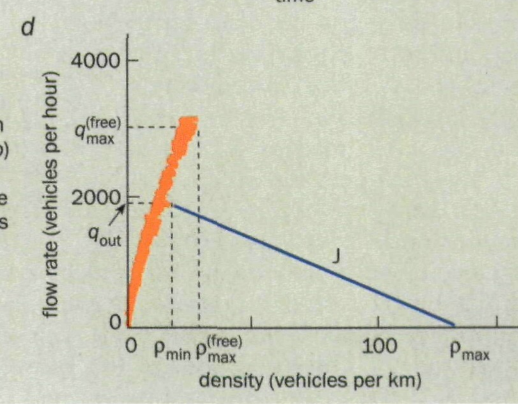
In 1974 Rainer Wiedemann at Karlsruhe University in Germany, building on work done by Ernst Todosiev of Ohio State University in the 1960s, developed a "psycho-physical" model in which a complex set of rules governs the reaction of the driver to the motion of other cars. And in the 1990s several models based on "cellular automata" have been proposed. In these models the road is divided into cells that are approximately 7 metres long: each cell can only contain one vehicle and these move and overtake according to a set of rules. This approach has been pioneered by Kai Nagel of the Los Alamos National Laboratory in the US and by Michael Schreckenberg of the University of Duisburg in Germany and co-workers.

One of the important characteristics of a traffic-flow model is the dependence of the average vehicle speed on the density of vehicles on the road. This dependence is built into most models, although some are able to predict it explicitly. This

2 A traffic jam in action



(*a*) Traffic flow on a section of the A5-South as a function of time and distance between 6.30 a.m. and 8.30 a.m. on Tuesday 23 June 1998. Red represents high rates of traffic flow and the pale blue valley shows the traffic jam. This section of road includes an intersection with another highway around the 23 km mark. A traffic jam formed near this intersection around 7.00 a.m. (top left) and then propagated back along the highway (i.e. upstream) over a period of about 80 minutes. The jam reached a detector at the 7.9 km mark just after 7.45 a.m., as can be seen in the plots of flow rate (*b*) and average speed (*c*). When the free-flow rate at this detector is plotted against the vehicle density (for the left lane), the data lie on a curve with a positive gradient (*d*). The end of this curve defines the maximum flow rate in free traffic, $q^{(free)}_{max}$, and the maximum vehicle density, $\rho^{(free)}_{max}$. However, traffic jams can form when the density exceeds ρ_{min}, which occurs at a flow rate q_{out}. The blue line connecting this point with the point at which the flow rate falls to zero is called the J line. The slope of this line has units of velocity and the value of the slope, which is typically between −12 km per hour and −18 km per hour, corresponds to the speed with which the downstream front of the jam moves against the traffic. It should be noted that the J line is not a part of the fundamental diagram for the congested-flow regime.



dependence is related to an obvious result observed in real traffic flow: the more vehicles on the road, the lower the average speed with which they move. The product of the vehicle density and the average speed is called the flow rate. When the flow rate is plotted as a function of vehicle density, we have what is known as the "fundamental diagram of traffic flow". It is obvious that this curve should pass through the origin (when the density is zero, so is the flow), and should have at least one maximum.

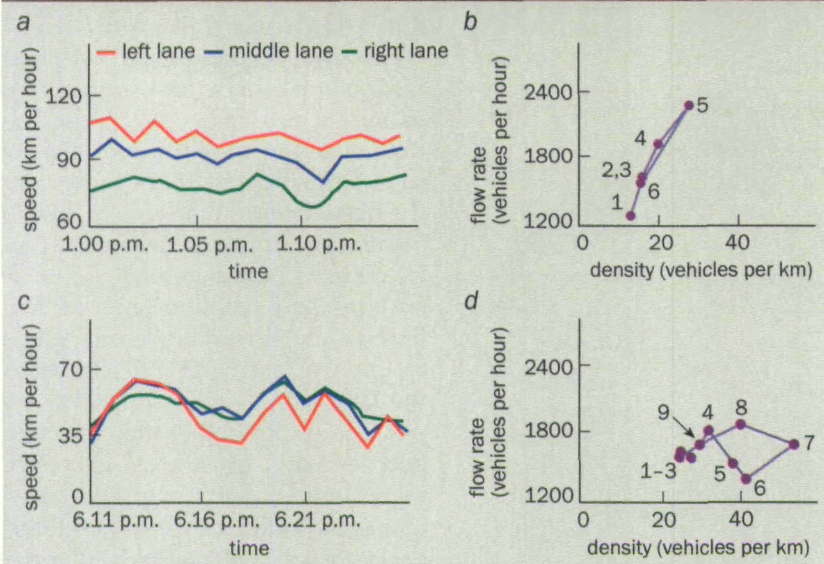
According to many traffic scientists the fundamental diagram consists of two isolated curves in the flow-rate–density plane: a curve with a positive slope for free traffic flow, and a curve with a negative slope for congested traffic flow (see the book by May in further reading). This means that if a local perturbation occurs in the density, vehicle speed or some other variable during free flow, the perturbation will propagate in the direction of the flow: that is with a positive velocity. In congested flow, however, the perturbation will propagate against the flow. These perturbations can sometimes be seen as waves in the traffic flow.

Two qualitatively different scenarios for the formation of traffic jams have emerged from these different mathematical approaches. As long ago as 1958 Herman, Montroll and others at General Motors in the US applied ideas from statistical physics – such as instabilities, critical points and so forth – in an attempt to explain why traffic jams form. They proposed that due to the finite reaction time of drivers, there should be a range of densities where the traffic cannot flow freely because of instabilities and phase transitions. In this model, traffic jams form spontaneously once the vehicle density exceeds a certain value.

A different scenario for jam formation was proposed in 1994 by the author and Peter Konhäuser at DaimlerChrysler. Below the density range for the formation of traffic jams, we proposed that there should be a broad range of lower vehicle densities where seemingly homogeneous and stable states of free traffic flow are in fact metastable. A metastable state is a state that is stable with respect to small fluctuations. However, if the amplitude of a local fluctuation exceeds some critical amplitude, it will grow and lead to the formation of a jam. This concept has subsequently been included in a large number of theories and models of traffic flow. These include models based on different microscopic approaches, including cellular automata (see Barlovic *et al.*, Helbing and Schreckenberg, and Krauß *et al.* in further reading), the optimal-velocity model of Bando and co-workers, and approaches in which the traffic is modelled as a gas (see Lee *et al.*, Mahnke and Kaupuzs, and Treiber *et al.*).

Some aspects of the phase transitions between the different phases of traffic are similar to the phase transitions between the solid, liquid and gas states. However, the actual phases are different: the gas state, for example, is an equilibrium state,

3 Free and synchronized flow



(*a*) The average vehicle speed for the three lanes of the A5-North between 1.00 p.m. and 1.15 p.m. on Friday 25 August 1995, and (*b*) the flow rate per hour versus vehicle density on the left lane between 1.08 p.m. (point 1) and 1.13 p.m. (point 6). This is free flow. (*c*) Average speeds between 6.11 p.m. and 6.26 p.m. on the same day, and (*d*) flow rate per hour versus density in the left lane between 6.12 p.m. (point 1) and 6.20 p.m. (point 9). The synchronized flow can be clearly seen in (c), and the difference between free flow and synchronized flow is obvious from a comparison of the flow-rate–density plots.

whereas the various phases of traffic are not in equilibrium and can exhibit a wider range of behaviour. This includes the spontaneous formation of spatial-temporal patterns that are, in a general sense, similar to those observed in low-temperature plasmas, chemical reactions, lasers and other non-equilibrium systems.

How well do these theories really explain the phenomena observed in traffic flow? The agreement between theory and experiment is good for the characteristic parameters of traffic flow, such as the velocity of the "downstream front" of the jam (see below), and the metastability of free flow with respect to the jam formation. However, the theories do not predict – and they still cannot explain – important features of various phase transitions and spatial-temporal traffic patterns that have been observed in real traffic flow by the author in collaboration with Hubert Rehborn.

The physics of the phase transitions, spatial-temporal patterns and other nonlinear phenomena observed in real traffic, and recent qualitative explanations by the author, are covered in the remainder of this article.

The three phases of traffic

Most of the results that I will describe are based on data taken for traffic on a busy section of the A5-South highway near Frankfurt in Germany. The A5-South connects Giessen in Germany with Basel in Switzerland, and is particularly busy near Frankfurt. Double induction-loop detectors measure the velocity of every vehicle on this part of the highway, and a computer calculates the flow rate and the average vehicle speed in one-minute intervals for each lane of traffic (figure 1). Some results are based on data taken on the A5-North. All these experimental data have been made available by the Board for Road and Transportation in the state of Hessen.

If the vehicle density is low enough, it is easy for vehicles to pass or overtake each other on multi-lane roads. This leads to "free flow" in which the average vehicle speed may be different for each lane. On the other hand, if the density is high enough, the flow becomes congested and traffic jams can form (figure 2). This situation will be familiar to all drivers.

However, in 1996 the author, in collaboration with Hubert Rehborn, discovered that two different phases of traffic flow were possible in the congested regime: synchronized flow and traffic jams. The discovery of synchronized flow – in which the vehicles in different lanes move with almost the same speed – meant that existing traffic models had to be revised to take account of the three phases of traffic flow: free flow, synchronized flow and traffic jams. The discovery of synchronized flow continues to have a major impact of the development on new traffic models.

Let us take a closer look at the differences between free flow and synchronized flow (figure 3). The low vehicle density in free flow makes it easy for vehicles to overtake each other, so the average speed for each lane tends to be different. Above a certain density, however, overtaking is not so easy, so vehicles move with almost the same average speed in the different lanes. This is synchronized flow. Although the average vehicle speed in synchronized flow is low, the flow rate can be as high as in free flow. In a traffic jam, on the other hand, the vehicle density is very high, but both the vehicle speed and the flow rate are very low, sometimes even zero (figure 2).

In synchronized flow, fluctuations in speed can be noticeably smaller in amplitude than in free flow because the vehicles tend to bunch. In free flow an increase in the vehicle density is also accompanied by an increase in the flow rate, and vice versa. In synchronized flow, however, changes in the flow rate and the density can be totally non-correlated. An increase in the vehicle density can be accompanied by either an increase or by a decrease in the flow rate (figure 3*d*).

The dynamics of synchronized flow are completely different to those observed in both free flow and jams. For example, whereas any waves in the density or speed of vehicles in free flow always have positive velocities (i.e. they move in the same direction as the flow of traffic), the waves in synchronized flow can have either positive or negative velocities. This is linked to another experimental result: free flow can be represented by a curve with a positive slope in the flow-rate–density plane; synchronized flow, on the other hand, exists over a relatively wide two-dimensional region of the plane. That is, for a given density, a range of flow rates (or speeds) is possible, and vice versa (figure 4*a*). Therefore there is no fundamental diagram that can describe synchronized flow. This could be one of the main reasons why mathematical models still cannot explain many of the experimental features of the phase transitions observed in real traffic flows.

There are in fact three types of synchronized flow: the complex synchronized flow described above and two others. In homogeneous synchronized flow, both the average speed and the density are uniform over space and stationary over time. In so-called homogeneous-in-speed synchronized flow, however, only the average speed exhibits this behaviour: the density, and therefore the flow rate, can change noticeably in both space and time. One may treat all types of synchronized flow as one phase of traffic, however, because the probability of overtaking is low in all three types and they cover approximately the same two-dimensional region in the flow-rate–density plane (figure 4*a*).

Characteristics of traffic

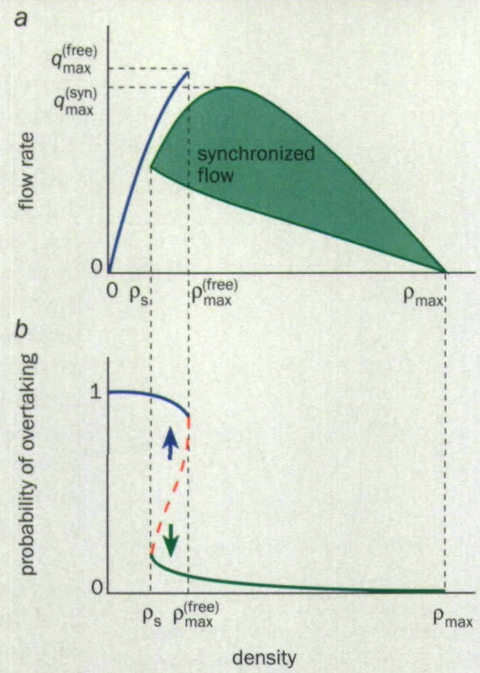
A driver stuck in a traffic jam is only interested in one question: "How long is the traffic jam?" The length or "width" of the jam is defined as the distance between its upstream and downstream fronts. The "upstream" front, which is at the back of the jam, is due to vehicles slowing down as they join the jam. The "downstream" front at the head of the jam is due to vehicles accelerating as they escape the jam. A wide jam is one where the width is considerably larger than the widths of these fronts.

An important difference between synchronized flow and traffic jams is that the former does not have any "characteristic parameters". However, if the vehicles leaving a wide jam move into a region of free flow, the jam will possess the following characteristic parameters: the mean velocity of the downstream front, the vehicle density inside the jam, the flow rate out of the jam, and the speed of free flow of the vehicles that have escaped the jam. It should be noted that the maximum flow rate in free flow is about 50% greater than the flow rate out of a wide jam.

These parameters are characteristic in the following sense: they do not depend on initial conditions in traffic flow; they are the same for different wide jams; and they do not change over time. And they remain characteristic as long as vehicles leaving the jam enter the free-flow phase and various control parameters (such as the weather, the percentage of long vehicles or the number of lanes on the highway) do not change. Free flow is also thought to have several characteristic parameters: the maximum flow rate that can be achieved and the maximum vehicle density possible in free flow. The identification of characteristic parameters is a common theme in statistical-physics research and helps to improve our understanding of the system we are dealing with.

It must be noted that one of the characteristic parameters, ρ_{min}, the vehicle density that corresponds to the flow rate out of a wide jam (q_{out}), determines the threshold for jam formation in free flow. Traffic jams cannot form at vehicle densities below this density, but free flow is metastable with respect to jam formation above ρ_{min}. This behaviour can be summarized on the flow-rate–density plane (figure 2*d*).

4 Metastable states



Experimental observations suggest that phase transitions in traffic can happen in two qualitatively different ways: the "free flow → synchronized flow" method (shown here); and either the "free flow → jam" or "synchronized flow → jam" method (not shown). (*a*) The phase transition from free flow (blue curve) to synchronized flow (green region) is related to changes in the probability of overtaking. (*b*) This probability is described by a Z-shaped curve: it is high for free flow (blue) because there is a large difference between vehicle speeds in the different lanes, and low for synchronized flow (green curve) because the speeds in the different lanes are quite similar. For vehicle densities between the minimum density for synchronized flow, ρ_S, and the maximum density possible in free flow, $\rho_{max}^{(free)}$, both free and synchronized flow are possible with the probability of overtaking depending on which phase the traffic flow is in. However, if the amplitude of a local fluctuation in one of the variables describing the traffic (e.g. the density or speed) exceeds some critical amplitude, the probability of overtaking in free flow will fall below the curve in this overlap region, and the probability of overtaking will then continue to decrease and a "free flow → synchronized flow" phase transition will occur (down arrow). Otherwise the initial perturbation will fade away and the flow will remain free (up arrow). A different effect, which is linked to the finite reaction time of drivers, is responsible for the "free flow → jam" and "synchronized flow → jam" phase transitions (see Kerner 1998 and 1999 in further reading).

However, experimental observations of real traffic have shown that jams only form in free flow if the formation of the synchronized phase is somehow hindered. In the most cases the phase transition from free flow to synchronized flow is observed instead. It can even be shown that the existence of the maximum point of free flow in the flow-rate–density plane ($q_{max}^{(free)}$ and $\rho_{max}^{(free)}$ in figure 2*d*), is linked to the "free flow → synchronized flow" phase transition rather than the "free flow → jam" transition. Therefore there are two different phase transitions with different threshold densities and it is a challenge to discover the differences between them. Although this contradicts the results of all the mathematical models and seems to be highly counter-intuitive, it is an experimental result that is observed in real traffic flow. How can these experimental results be explained?

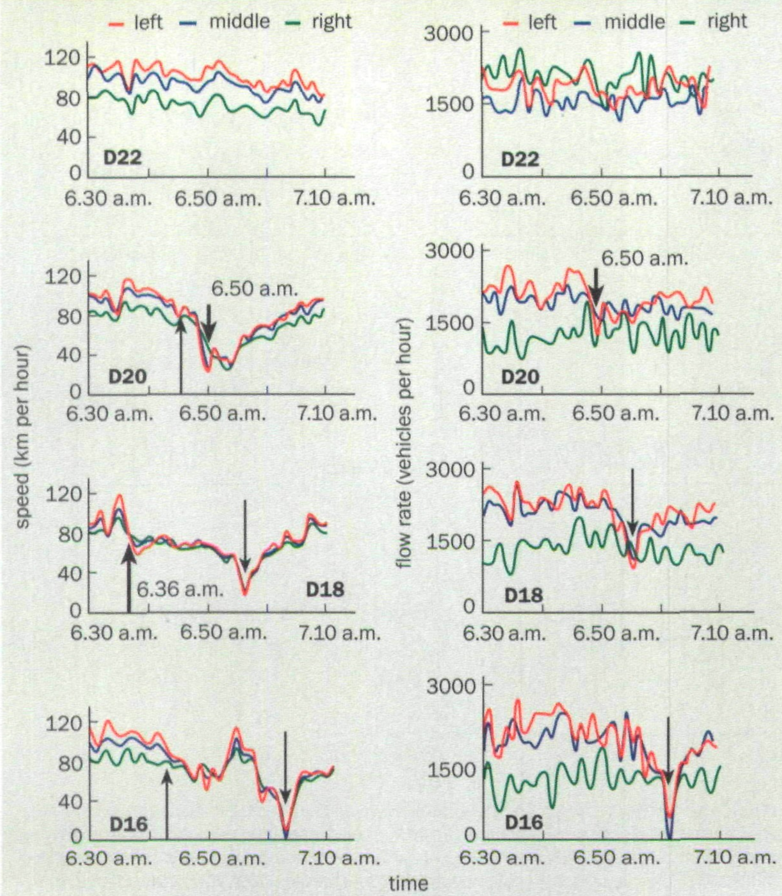
Complexity and phase transitions

The existence of three qualitatively different phases of traffic flow – free flow, synchronized flow and wide jams – means that three types of phase transition are possible in traffic flow: "free flow ↔ jam", "free flow ↔ synchronized flow", "synchronized flow ↔ jam(s)". Understanding the various phase transitions between these three states plays a key role in understanding the behaviour of real traffic flows. Experimental studies have shown that all three are local first-order phase transitions.

A local first-order phase transition in a metastable state occurs only if a local perturbation exceeds some critical amplitude. As in physical systems, the phase transition in traffic flow is accompanied by a jump in one or more of the variables that describe traffic flow (e.g. the vehicle density, average speed or flow rate) and a hysteresis effect. Other common properties of first-order phase transitions are: (i) the critical amplitude is largest at the threshold that separates the stable and metastable states of the system, and it decreases as you move away from the threshold value and into the metastable region; (ii) the lower the amplitude of the critical perturbation, the higher the probability of a spontaneous phase transition.

However, these phase transitions also possess qualitatively different features. For example, during the "free flow → synchronized flow" phase transition, the vehicle speed decreases sharply whereas the flow rate can remain almost as

5 Traffic jams without bottlenecks



The speed (left) and flow rate (right) on the A5-South highway between 6.30 a.m. and 7.10 a.m. on Monday 17 March 1997. The "free flow → synchronized flow" phase transition can be seen as a sudden drop in speed recorded by the D18 detectors at 6.36 a.m. (up arrow) even though there is free flow in the vicinity of the intersections with the I2 (D16) and I3 (D22). The transition to synchronized flow can also be seen in the synchronization of the vehicle speeds in different lanes while the flow rate does not change noticeably. The region of synchronized flow moves both upstream (D16, up arrow) and downstream (D20, up arrow). The pinch effect can be seen as an increase in the vehicle density in the left lane at D20 from about 31 vehicles per kilometre of road between 6.45 a.m. and 6.48 a.m. to about 46 vehicles per kilometre during the period 6.49 a.m. to 6.54 a.m. (To obtain the vehicle density one has to divide the flow rate by the speed.) The velocity also drops from about 80 km per hour to about 40 km per hour. A local perturbation then occurs in the pinch region at D20 at 6.50 a.m. (down arrow) and propagates upstream causing traffic jams to form, first seen at D18 and then at D16 (down arrows). During this time the traffic at the intersection with the I3 (D22) remains unaffected.

high as in an initial free flow. On the other hand, in the "free flow → jam" transition, both the average speed and the flow rate sharply decrease to zero. Changes in the spatial-temporal patterns of traffic flow caused by these phase transitions, and the rich dynamical behaviour of synchronized flow, are responsible for the complexity of real traffic flow observed in experiments.

As mentioned above, experimental observations suggest that jams rarely form in free flow. Instead the free flow becomes synchronized, and a jam forms in the synchronized flow. This suggests that the critical amplitude of local perturbations needed to cause the "free flow → synchronized flow" transition is much lower than that needed to cause a "free flow → jam" transition under the same conditions.

To explain this, let us assume that a "free flow → synchronized flow" phase transition occurs if a local perturbation in the density or speed (for example caused by a driver unexpectedly changing lane) causes the probability of a vehicle being able to "overtake" to fall below some value (figure 4*b*). The critical amplitude of perturbation needed to significantly reduce the probability of overtaking can be considerably lower than that needed to cause a "free flow → jam" phase transition. Indeed, the initial perturbation does not have to increase, it must only cause the probability of overtaking to fall. In contrast, for a "free flow → jam" transition to occur, the amplitude of the perturbation itself (that is the change in vehicle density or speed) must grow during the free-flow phase. This interpretation offers an explanation for some of the puzzling features observed in real traffic, in particular the fact that the "free flow → jam" phase transition rarely occurs.

So how does a jam emerge in free flow? The first step is a "free flow → synchronized flow" phase transition. The second step is known as the "pinch effect". In this process the synchronized flow compresses itself into a very high density state in which spontaneous local perturbations are very likely to grow and lead to the formation of a traffic jam, as can be seen in real data for the A5-South (figure 5).

Bottlenecks

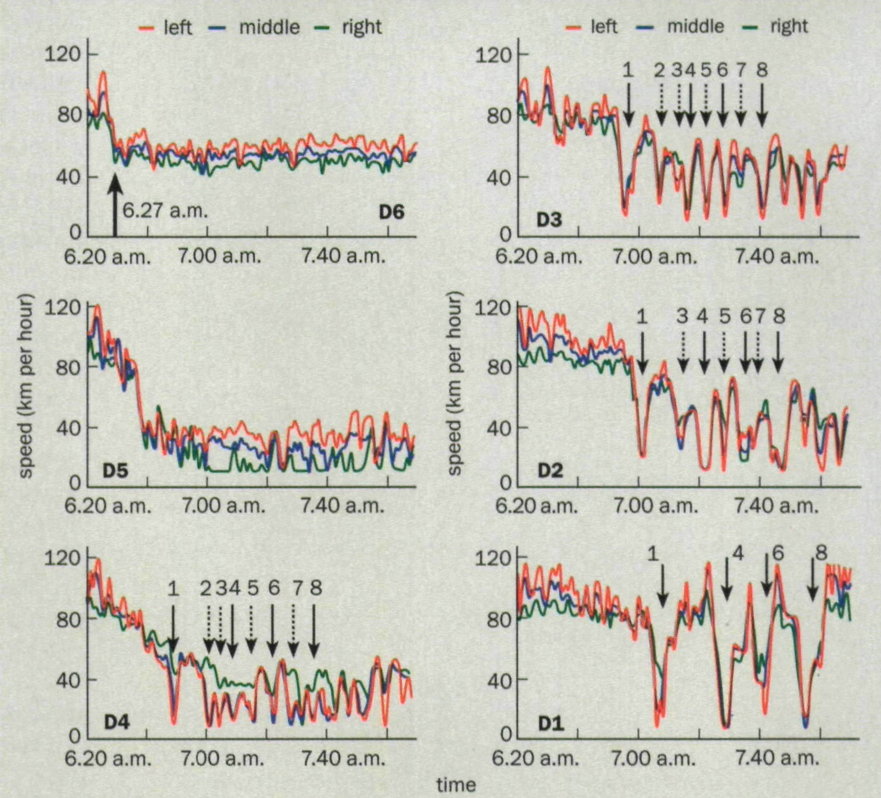
The fact that the "free flow → synchronized flow → jam" transition can occur spontaneously (that is in the absence of on-ramps, off-ramps or bottlenecks) shows that phase transitions in traffic flow are linked to some intrinsic nonlinear properties of the flow. However, just as defects and impurities are important in physical systems, so are permanent non-homogeneities, such as on- and off-ramps, and temporary bottlenecks, such as roadworks, in traffic flow. Observations show that these features can trigger phase transitions, which is why synchronized flow and traffic jams are considerably more likely to form near on- and off-ramps.

When synchronized flow occurs outside bottlenecks, the boundaries of the flow may propagate both upstream and downstream. Therefore, the pinch effect and the associated traffic jam can happen downstream from where the synchronized flow first appeared. Again this is highly counter-intuitive but it happens in real traffic flows.

However, when the "free flow → synchronized flow" transition occurs in the vicinity of an on-ramp, as happens quite often, any pinch effect will only be observed upstream from the ramp, as we would expect. One effect of this phase transition will be that the average speed of vehicles in the lane joining the highway, and in the other lanes as well, will be considerably lower than in free flow, although the flow rates will remain high. This is because the relatively high flow rate of slow-moving vehicles squeezing onto the highway forces the drivers already on the road to slow down, which in turns keeps the speed of vehicles joining the highway low. As a result, the downstream boundary of the region of synchronized flow remains fixed near the on-ramp, and the synchronized region upstream is self-maintained for several hours. This allows ample time for the pinch effect to lead to the formation of traffic jams, including the series of short traffic jams along a road known as "stop-and-go traffic". Indeed, experimental observations suggest that stop-and-go traffic can only happen when a region of synchronized flow exists for a long enough time. In contrast, when the "free flow → synchronized flow" phase transition occurs outside a ramp or bottleneck, it only lasts for about 30 minutes or less.

In some ways stop-and-go traffic happens in the same way that the pinch effect can lead to traffic jams in the absence of bottlenecks (figure 5). First the pinch effect occurs in synchronized flow, then a growing local perturbation self-emerges and causes a jam to form. The difference in stop-and-go traffic is that a lot of local perturbations grow and gradually transform into narrow jams in the pinch region. (In contrast to a wide jam, a narrow jam consists of only upstream and downstream fronts: vehicles do not come to a stop inside the narrow jam.) This can only happen if the pinch region exists for a long time. It turns out that the narrow jams can move upstream (i.e. against the traffic) faster than the downstream front of any wide jam, which leads to the formation of a series of wide jams with their downstream fronts about 2.5–5 km apart. Again this can be seen in real data from the A5-South (figure 6).

6 Stop-and-go traffic



The vehicle speed at six points on the A5-South highway between 6.20 a.m. and 8.10 a.m. on Monday 13 January 1997. First, the "free flow → synchronized flow" phase transition near the on-ramp (D6) can be seen as a sudden drop in the speed at 6.27 a.m. (up arrow), and as a synchronization of the vehicle speed in the different lanes. The flow rate (not shown) does not change noticeably. Then a wave of induced "free flow → synchronized flow" transitions upstream can first be seen as a sudden drop in the speed recorded by the D5 detectors at 6.38 a.m. Simultaneously, the pinch effect leads to a further drop in speed at D5 and D4 in comparison with the speed at D6. The emergence of narrow jams in the pinch region can be seen as a sequence of local drops in the speed (and flow rate) recorded by the D4 detectors (down arrows 1–8). The narrow jams grow in amplitude and propagate back upstream (i.e. against the flow) and one of them will form a wide jam (solid down arrows 1; D4–D1). Two events can happen after the first wide jam has formed: (i) other narrow jams can catch up and merge with the wide jam; and/or (ii) the further growth of the narrow jams nearest the wide jam is damped (dotted down arrows 2, 3; D4–D2). A narrow jam must be well downstream of the first wide jam if it is to grow into a second wide jam (solid down arrows 4; D4–D1). After the second wide jam has been formed, the process repeats itself (dotted down arrows 5 or 7; D4–D2). The end result is a stop-and-go sequence of wide jams with 2.5–5 km between their downstream fronts. This is much longer than the mean distance between narrow jams. This sequence of wide jams may then propagate upstream, many kilometres away from the where the jams first formed.

Outlook

The physics of traffic flow is proving to be much richer than most physicists working in the field had expected. Recent experimental observations of real traffic patterns have discovered new phases of traffic flow, such as synchronized flow, and revealed a large number of features that are qualitatively similar to those observed in other nonlinear systems. The next challenge for physicists in this field is to develop new mathematical and theoretical concepts to explain these features. It seems inevitable that as our roads get busier, so too will the physicists who are trying to understand and explain why the traffic on these roads behaves the way that it does.

Further reading

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