Traffic Data

Representation of Cross-Sectional Data

Introduction

In this lecture, we discuss different visualizations of microscopic and macroscopic cross-sectional data and the possible conclusions that one can draw from them. Time series of aggregated quantities such as speed, flow, and density show temporal developments, while speed-density and flow-density diagrams allow us to make statements about the average driving behavior on the observed road segment.

Particularly the flow-density diagram contains so much information about the traffic dynamics that its idealized form is also called the fundamental diagram of traffic flow. If single-vehicle data is available, we can also obtain distributions of microscopic quantities (vehicle speeds, time gaps, etc.).

Time Series of Macroscopic Quantities

One way of representation is time series of some aggregated quantity, which has been measured at a cross-section. Flow, speed, and density time series of a few hours' data tell us about traffic breakdowns, types of traffic congestion (oscillatory or essentially stationary), and the capacity drop after a breakdown (Fig.1).

From the specific daily patterns of traffic demand (Fig.2), the reader can easily recognize whether it was recorded on a Monday, Tuesday/Wednesday/Thursday, Friday, or on a weekend. However, these daily traffic-demand plots are used primarily in transportation planning and are beyond the scope of this course.

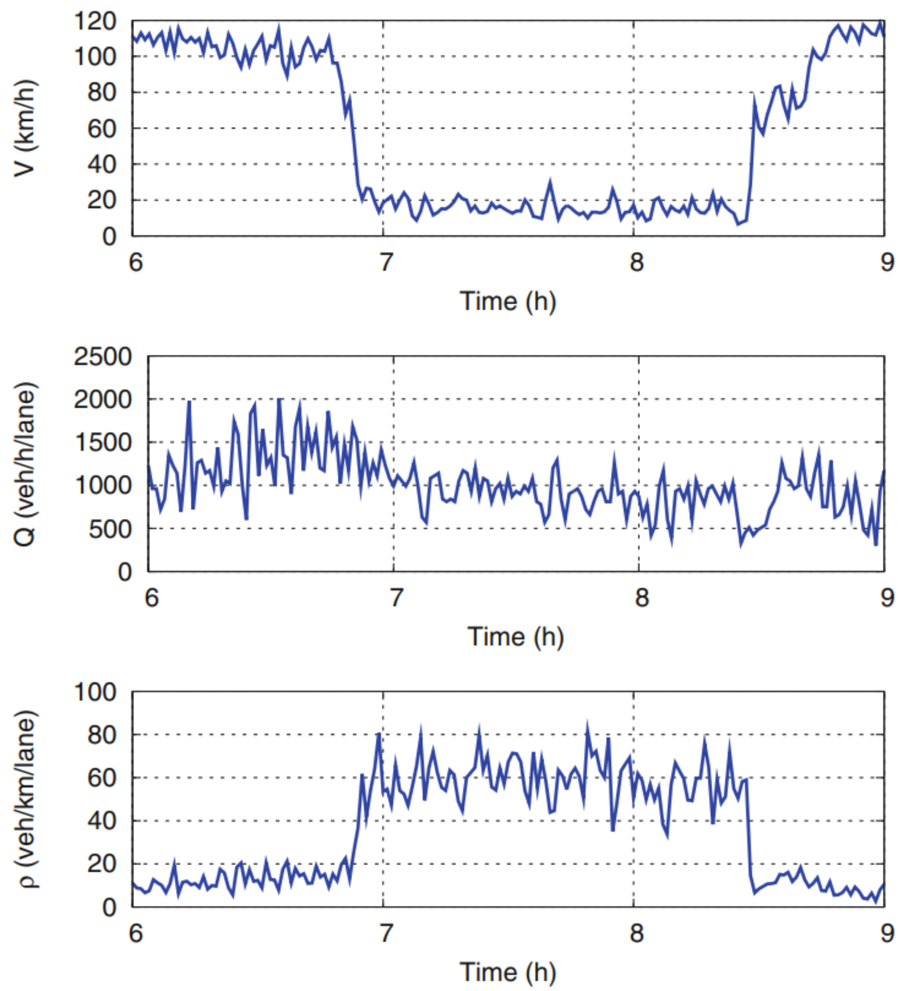

Fig. 1 Time series during the morning peak hour from one-minute data. From top to bottom: arithmetic mean speed V, flow Q, and estimated density $\rho = Q/V$.

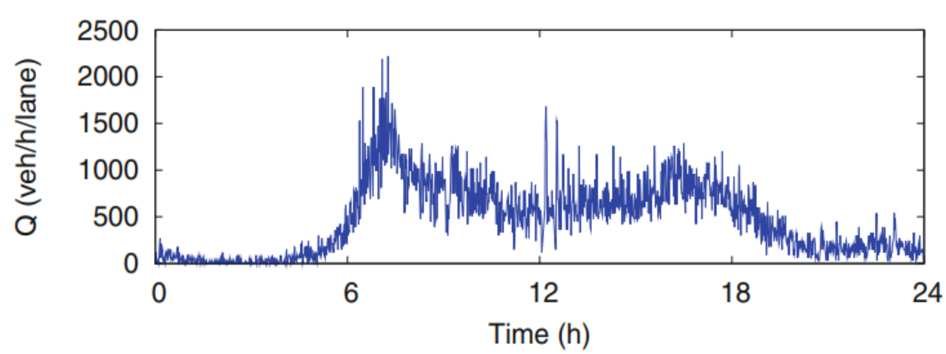

Fig. 2 Typical daily time series of the traffic flow (demand) on a weekday (Wednesday).

It is very easy to draw incorrect conclusions when interpreting traffic jam dynamics using single time series, as the following exercise illustrates:

Why is it wrong to conclude from the time series in Fig. 1 that the traffic breakdown occurred at around 7 a.m.? Can we at least conclude (from the figure) that vehicles near the cross-section at 7 a.m. decelerate, or that vehicles near the cross-section at 8.30 a.m. accelerate? If not, what are alternative explanations for the observed patterns?

Sol.

According to Fig. 3, the speed drop shortly before 7 a.m. is an upstream jam front that is moving upstream. Alternatively, it could be a downstream jam front moving downstream (with the driving direction) that is caused by a moving bottleneck, e.g., by an oversize load. However, this case is rather unlikely, so we assume that it is an upstream jam front and vehicles are braking to avoid a rear-end collision. The rise in the speed at 8.30 a.m. can be explained by two different scenarios:

(i) It is a downstream-moving upstream front, i.e. the traffic jam shrinks. This would imply that, after 8.30 a.m., vehicles are braking shortly after passing the detector, while the time series indicates an acceleration.

(ii) Alternatively, it could be an upstream-moving downstream front, caused for example by a disappearing temporary bottleneck (road block, traffic light, etc.) as the waiting vehicles subsequently start to move again. In this case, the vehicles accelerate as indicated by the time series. For both scenarios, we can estimate the jam front velocity directly from the fundamental diagram.

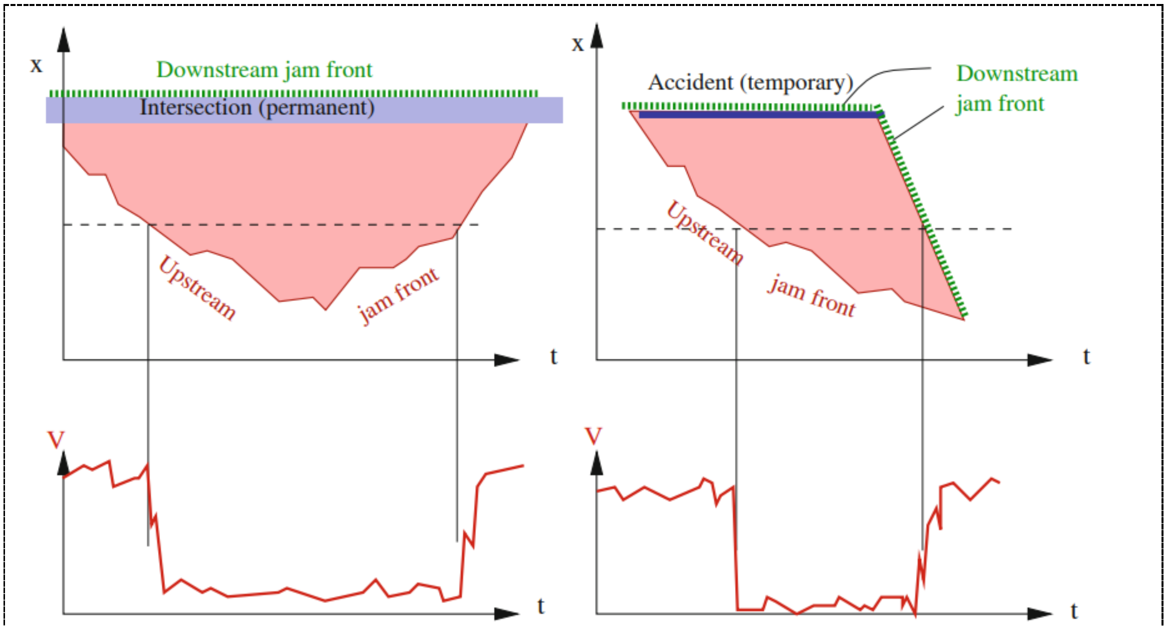

Fig. 3 Typical daily time series of the traffic flow (demand) on a weekday (Wednesday).

Speed-Density Relation

If we plot the aggregated vehicle speed over traffic density we obtain a speed-density diagram (cf. Fig. 4). We see that the average speed is lower in denser traffic. Furthermore, the diagram reflects the average behavior of a (typical) driver-vehicle unit in different densities and external influences such as speed limits, weather conditions, etc.

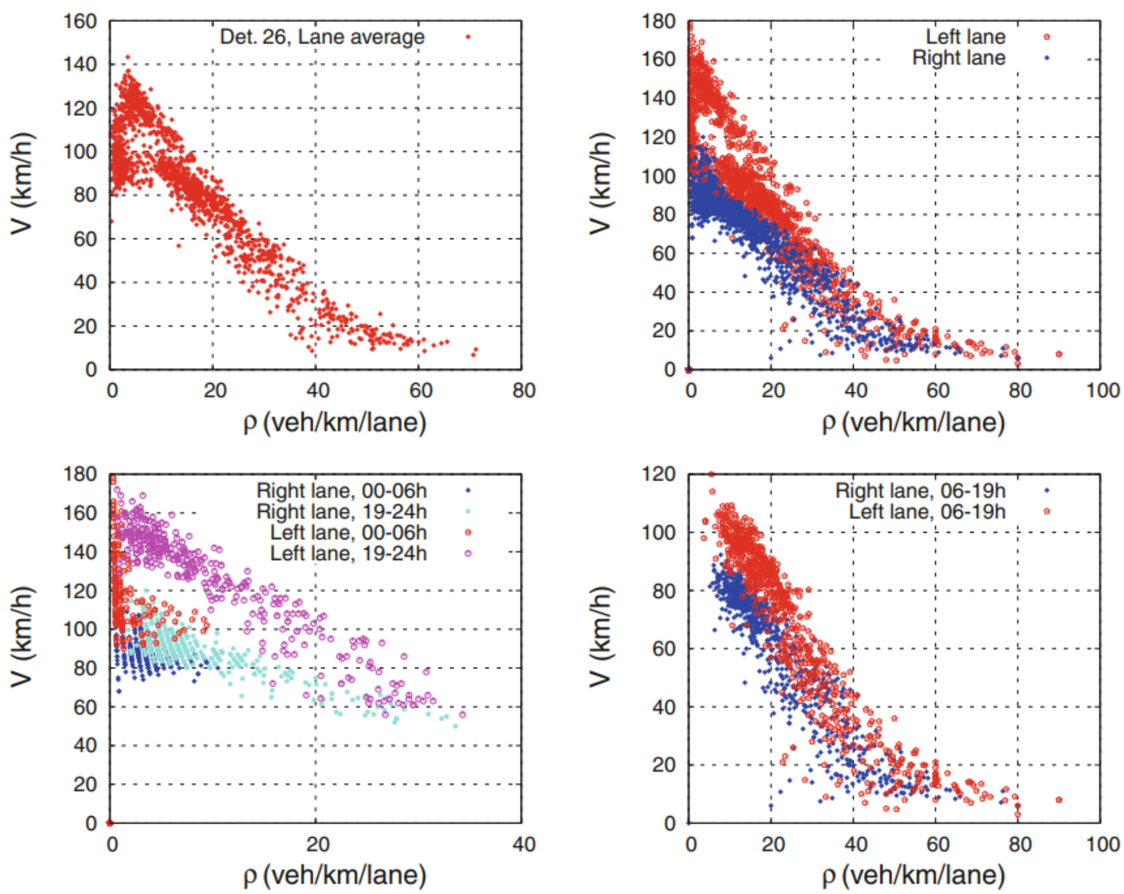

Fig. 4 Speed-density relation obtained from one-minute data collected on the Autobahn A9 near Munich, Germany, using the average over both lanes (top left), individual averages of both lanes (top right), and individual lane averages conditioned on the night (bottom left) and day hours (bottom right).

In very low-density traffic, the drivers are usually not influenced by other vehicles and we obtain the average free speed V_0 for $\rho \to 0$ (cf. Fig. 5). This speed is the minimum of

- The actual desired speed of the drivers,
- The physically possible attainable speed,
- An administrated speed limit (plus the drivers' average speeding). However, V_0 is often directly referred to as the desired speed.

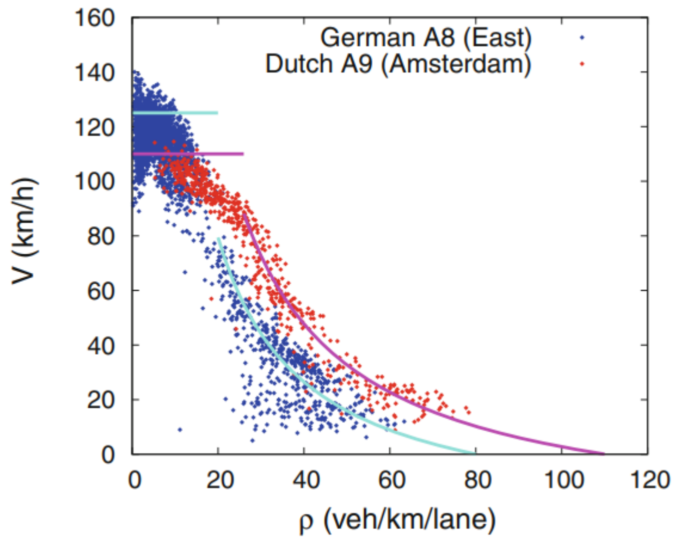

Fig. 5 Speed-density diagrams, averaged over all lanes, for segments of the Dutch A9 (Haarlem to Amsterdam) and the German A8 (Munich to Salzburg, Austria).

To approximately obtain the distribution of desired speeds from empirical data, we can use the speed distributions in single-vehicle data of low-density traffic (Fig. 6). In this case, there are few interactions between the drivers, and most of the drivers can be expected to drive at their desired speed. The distributions of speeds on the left and middle lanes are symmetric and approximately Gaussian, while speeds on the right lane are distributed bimodal, showing the superposition of the different speed distributions of trucks and passenger cars. Figure.7 shows average speed differences between lanes. In denser traffic, the speed difference tends towards zero, leading to a speed synchronization of the lanes.

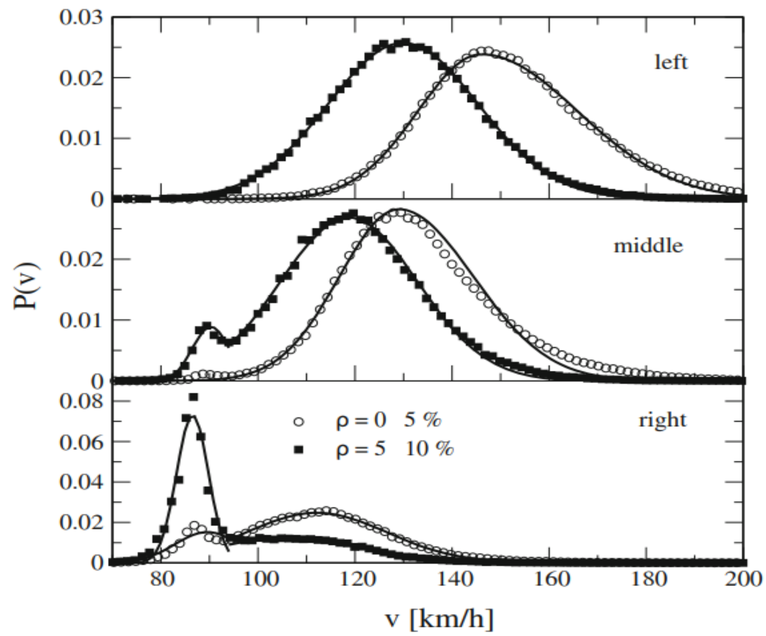

Fig. 6 Probability distributions of the vehicle speed, P(v), in low-density traffic on the German Autobahn A3 (three lanes in each direction) [From Knospe et al., Physical Review E 65, S. 56133 (2002)].

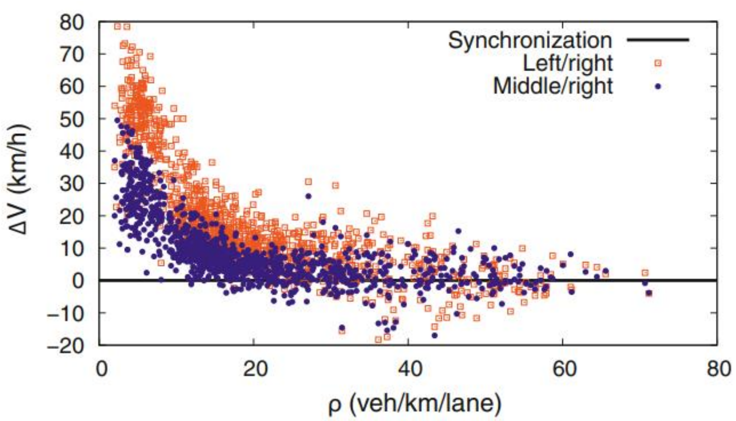

Fig. 7 Difference in average speed between neighboring lanes (A9-South near Munich, Germany).

Speed-density diagrams might show heterogeneous traffic and different external conditions, which have to be considered when interpreting them. Examples include a varying percentage of trucks at different times of the day, different weather conditions (lighting, precipitation), and time-dependent speed limits issued by traffic control systems. This also applies to flow-density diagrams.

Distribution of Time Gaps

Using single-vehicle data, we can also obtain the distributions of time gaps, as shown in Fig. 8 for two different speed ranges corresponding to free and congested traffic. The time-gap distributions exhibit the following properties:

1. Time gaps are broadly scattered—it is not unusual to see standard deviations larger than the arithmetic mean $\langle T \rangle$i.e., a coefficient of variation greater than 1.
2. The distributions are strongly asymmetric. Both in free and congested traffic we observe time gaps longer than 10 s.
3. In free traffic (with speeds larger than some critical speed V_c) the most probable time gap $\hat{T}$(the statistical mode) is significantly smaller than in congested traffic. In both speed regimes, $\hat{T}$ is significantly smaller than the recommended safe time gap in the USA ("leave one car length for every ten miles per hour of speed"), or in Europe ("safety distance (in meters) equals speed (in km/h) divided by two", corresponding to 1.8 s).
4. The arithmetic mean is also significantly smaller in dense free traffic than in congested traffic.

The mean flow is equal to the inverse of the arithmetic mean of the time headways. Thus, we can also determine the flow decrease after a traffic breakdown from the distributions in Fig.8. Traffic jams usually do not dissolve quickly once they have emerged, due to this capacity drop.
Most of the observed time-gap distributions are not identical to the distribution of the drivers' desired time gaps but provide an upper bound only. The real-time gap is larger in free traffic because most vehicles are not following another vehicle. With a flow of, e.g., 360 veh/h per lane (corresponding to a mean headway of 10 s), the mode of the time-gap distribution is still below 1 s. There are also dynamic influences since the following vehicle might be "getting away" if the following vehicle cannot accelerate any further (or its driver does not want to). These effects explain, at least partially, the strong asymmetry of the distributions.

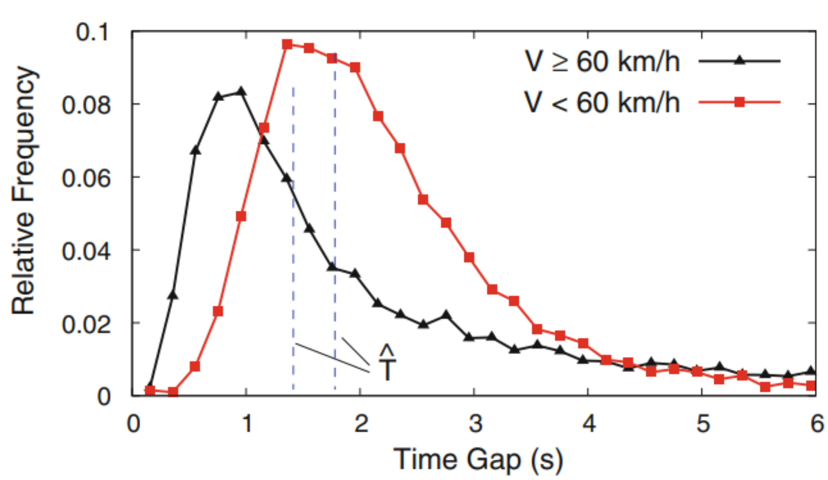

Fig. 8 Distribution of the time gaps in two speed regimes (free and congested traffic), measured on the Dutch A9.

Flow-Density Diagram

The flow-density diagram, i.e., plotting traffic flow against density, allows us to make several statements on the macroscopic (i.e., average) behavior of a driver-vehicle unit. In its idealized form, i.e., steady-state equilibrium of identical driver-vehicle units, it is also called a fundamental diagram. The following quantities can be derived from the fundamental diagram:

1. The desired speed equals the asymptotic gradient $Q\acute{(}0)$ of the fit Q(ρ)for ρ = 0. This quantity can be more accurately determined using speed-density diagrams.
2. The actual mean speed for a defined density is given by the slope Q(ρ)/ρ of the secant through (0, 0) and (ρ, Q(ρ)).
3. The maximum value of Q(ρ) is the road capacity per lane.
4. The inverse of the smallest nonzero density ρ_{max} for which $Q(\rho_{max}) = 0$ equals the average vehicle length plus the average gap between stopped vehicles.
5. The mean time gap T can be determined from the (negative) slope of Q(ρ) at large densities
6. The slopes of flow-density diagrams also allow us to read off the propagation velocities of jam fronts and variations of macroscopic quantities.

Bias concerning the fundamental diagram.

It is important to carefully distinguish between measured flow-density data and the fundamental diagram.

The fundamental diagram describes the theoretical relation between density and flow in stationary homogeneous traffic, i.e., the steady-state equilibrium of identical driver-vehicle units. The flow-density diagram represents aggregated empirical data that generally describes non-stationary heterogeneous traffic, i.e., different driver-vehicle units far from equilibrium.

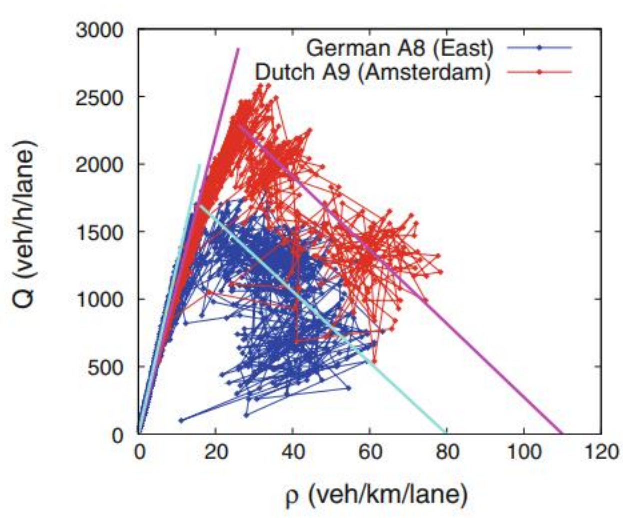

Fig. 9 Flow-density diagram (averaged over all lanes) for sections of the Dutch A9 (Haarlem to Amsterdam) and the German A8-East (Munich to the Austrian border) near Irschenberg.

There are multiple reasons for flow-density data not to coincide with the fundamental diagram:

- The measurement process induces systematic errors.
- The traffic flow is not at equilibrium.
- The traffic flow has spatial inhomogeneities or contains non-identical driver vehicle units.

The statements on traffic jam dynamics and driving behavior derived in the above enumeration are exact for the fundamental diagram, only. Since each of the aforementioned factors can cause significant differences between the density obtained from Eq. (14) (lect.2) and the theoretical expectation in the fundamental diagram (it is not unusual to see discrepancies by a factor of two), deriving statements from flow-density data is quite error-prone. The following examples of empirical flow-density relations are shown in Figs. 9, 11, and 12 (upper left panel), the maximum traffic density obtained by extrapolation is unrealistically small, while the front propagation velocities derived from the trend of flow-density point clouds of congested regions are too large in magnitude (and the point clouds do not always show a clear trend).

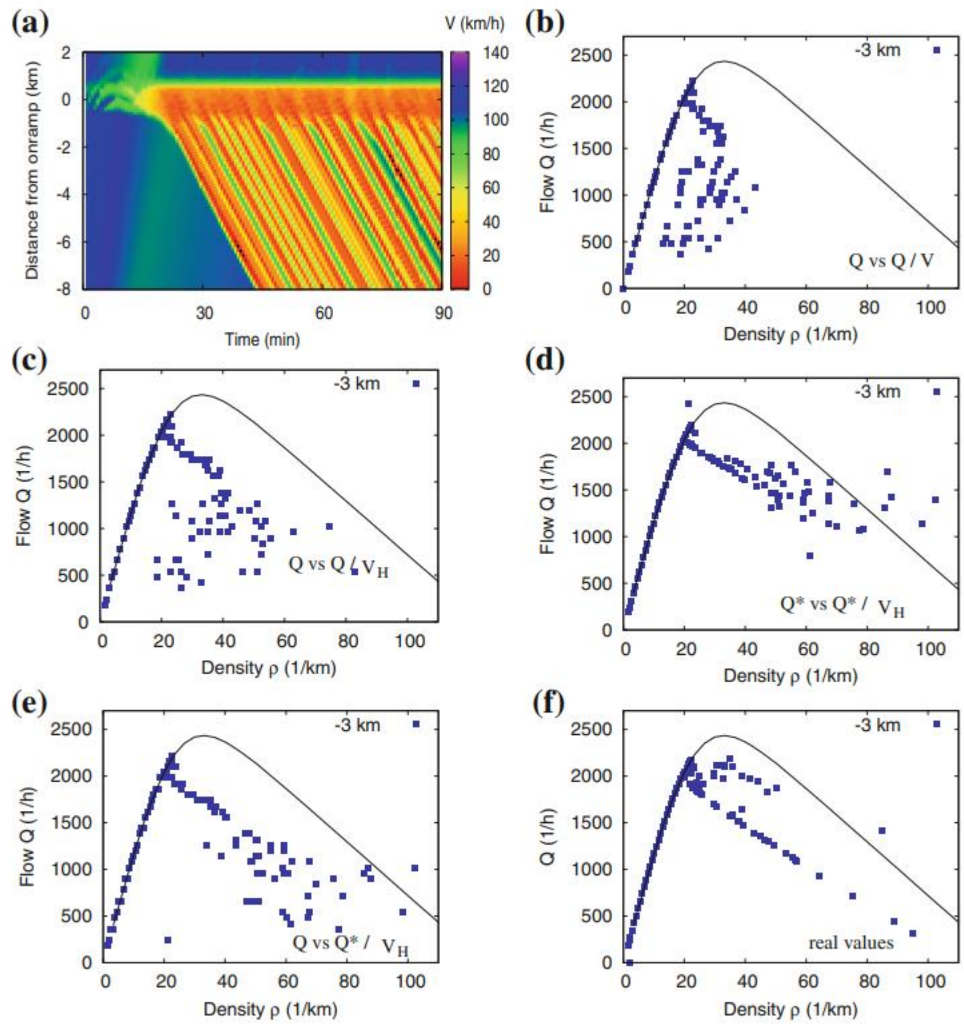

Fig. 10 Microscopic simulation of a traffic breakdown and stop-and-go waves caused by an on-ramp.

To estimate the effects of the errors mentioned above, we can use traffic simulations that also simulate the measurement process using virtual cross-sectional detectors. Fig. 10 shows that the flow-density diagram depends strongly on the method of averaging for obtaining the macroscopic speed and the flow, at least at large densities. Particularly, all methods yield estimated densities that strongly deviate from the actual density, which is, of course, available in the simulation. Remarkably, plotting the flow Q against the density estimate:

$$\rho^* = \frac{Q^*}{V_H} \qquad (1)$$

(Fig. 10e) consistently yields the least biased result in the simulations although the unbiased flow is given by the harmonic mean Q of the microscopic flow, and not by the arithmetic average $Q*$ (Eq.12) (Lec.2). In any case, the difference between the true flow-density points (f) and the data shown in (b)–(e) is caused by the measurement process. The difference between the flow-density data (f) and the fundamental diagram, however, is due solely to non-equilibrium effects. This can be concluded since identical driver-vehicle units were simulated. We finally notice that quantities that are derived purely from measurements of the flow, such as the capacity and the hysteresis effects to be discussed in the next paragraph, are less subject to errors.

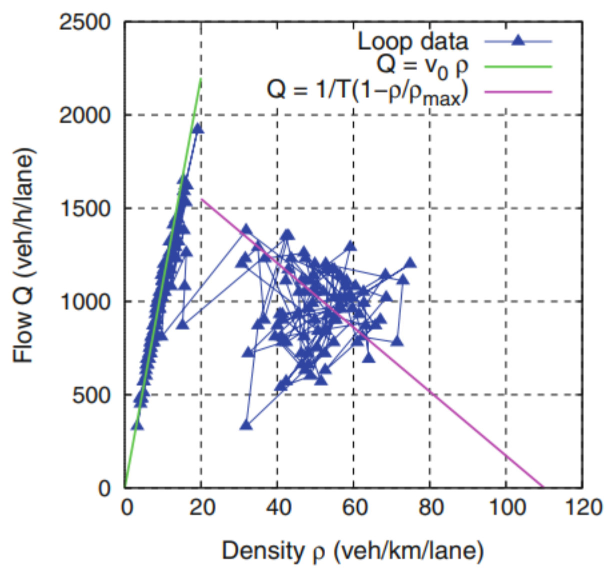

Fig. 11 Microscopic simulation of a traffic breakdown and stop-and-go waves caused by an on-ramp.

Capacity drop and hysteresis

A sudden drop in the maximum possible traffic flow (capacity drop) is sometimes observed with a traffic breakdown (Fig. 11 and 12). In this case, the traffic shows hysteresis effects, i.e., the dynamics depend not only on the traffic demand but also on the system's history. When the traffic breaks down, the system state switches from the "free branch" to the "congested branch", lowering the maximum possible flow. This implies that once a traffic jam has emerged, the traffic demand has to fall to a much lower value to dissolve the jam. The flow-density diagram describing this phenomenon is also said to have an inverse-λ form (due to its resemblance to a mirrored Greek letter lambda, λ).

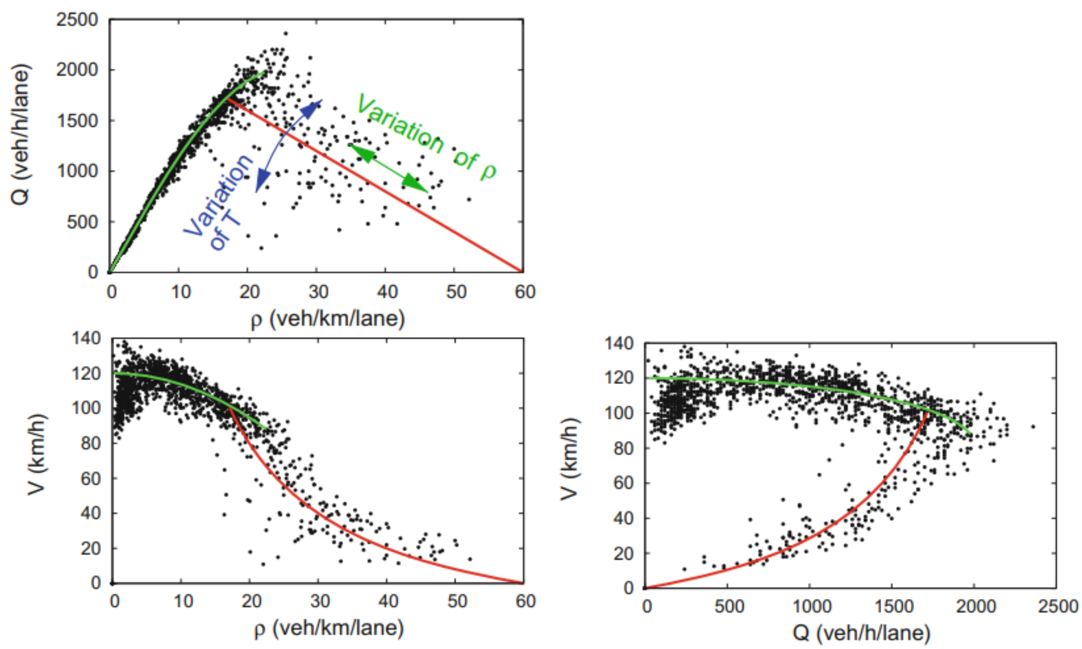

Fig. 12 Flow-density, speed-density, and speed-flow diagrams of the 1-minute data captured on the Autobahn A5 near Frankfurt, Germany using harmonic mean speed. The lines show the fit of a traffic-stream model.

Wide scattering

The strong variation of time gaps partially explains the strong scattering of the flow-density data in congested traffic: While in free traffic the variations of density and time gaps both cause variations of the flow-density data along the one-dimensional curve $Q \approx \rho V_0$, variations of density in congested traffic lead to changes in the flow-density data which are orthogonal to those caused by variation in the time gaps. Both effects combined lead to chaotic behavior of the flow-density data in congested traffic (Figs.11 and 12).

Finally, variations in the time gaps are not only caused by heterogeneous traffic (i.e., different desired time gaps of the individual drivers), but also by non-equilibrium traffic dynamics (i.e., the actual time gap is not equal to the desired time gap) and the systematic aggregation errors (Fig.10).

Speed-Flow Diagram

Plotting vehicle speed against traffic flow is also possible, of course. However, this diagram is not as fundamental for modeling as the flow-density diagram and not as demonstrative as the speed-density diagram. It does have the advantage of showing only directly observed quantities, nevertheless, it is also affected by systematic errors in speed aggregation. By the hydrodynamic relation $Q = \rho V$, all three diagram types are equivalent (Fig.12).

Example 1:

Derive and sketch both the speed-density diagram and the fundamental diagram, subject to the following idealized assumptions:

(i) All vehicles are of length L = 5m.

(ii) In free traffic (speed does not depend on other vehicles), all vehicles drive at their desired speed V_0= 120 km/h.

(iii) In congested traffic (speed is the same as the speed of the leading vehicle), drivers keep a gap of $s(v) = s_0 + vT$ to the leading vehicle, with the minimum gap s_0 = 2 m and the time gap T = 1.6 s.

Solution:

We have to distinguish between free and congested traffic.

Free traffic:

$V^{free}(\rho) = V_0 = const.$

Flow by using the hydrodynamic relation:

$Q^{free}(\rho) = \rho V^{free}(\rho) = \rho V_0$

Congested traffic: The speed-dependent equilibrium gap between vehicles, $s(v) = s_0 + vT$, leads to the gap-dependent equilibrium speed $V^{cong}(s)$:

$V^{cong}(s) = s - s_0/T$

Using the definition of the density ρ, we replace the gap s:

ρ= number of vehicles/ road length

= One vehicle/ one distance headway (front-to-front distance)

= 1 /vehicle length + gap (bumper-to-bumper distance)

$= \frac{1}{l+s}$

Thus s (ρ) = (1/ ρ) − l and therefore,

$V^{cong}(\rho) = \frac{s-s_0}{T} = \frac{1}{T}[\frac{1}{\rho} - (l + s_0)]$

The flow-density relation is obtained again by the hydrodynamic relation:

$Q^{cong}(\rho) = \rho V^{cong}(\rho) = \frac{1}{T}[1 - \rho(l + s_0)]$

The sum $l_{eff} = l + s_0$ of vehicle length and the minimum gap can be interpreted as an effective vehicle length (typically 7 m in city traffic, somewhat more on highways). Accordingly, the maximum density is:

$$\rho_{max} = \frac{1}{l+s_0} = \frac{1}{l_{eff}}$$

To obtain the critical density ρCseparating free and congested traffic, we determine the point where the free and congested branches of the fundamental diagram intersect:

$$Q^{cong}(\rho) = Q^{free}(\rho) \Longrightarrow \rho V_0 T = 1 - \rho(l + s_0) \Longrightarrow \rho C = \frac{1}{V_0 T + l_{eff}}$$

This is the "tip" of the triangular fundamental diagram, and the corresponding flow is capacity C (the maximum possible flow):

$$C = Q^{cong}(\rho C) = Q^{free}(\rho C) = \frac{1}{T}\left(\frac{1}{1+\frac{l_{eff}}{V_0 T}}\right)$$

The capacity C is of the order of (yet always less than) the inverse time gap T. The lower the free speed V_0, the more pronounced the discrepancy between the "ideal" capacity 1/T and the actual value.

Given the numeric values stated in the problem, we obtain the following values forρ_{max}, ρC, and C:

ρ_{max} = 143 vehicles/km, ρC = 16.6 vehicles/km,

C = 0.552 vehicles/s = 1,990 vehicles/h.