of the bottleneck (solid black squares) lie on the fundamental diagram itself. This apparent density increase near the outflow region of a congestion, also known as *pinch effect*, can be observed empirically. However, the systematic density underestimation, which conspicuously increases with the degree of the scattering of the data points, suggests that the *real* density increase is smaller, or even nonexistent. This means that the pinch effect is essentially a result of data misinterpretation, or, more specifically, by estimating the density with the time mean speed instead of the space mean speed (cf. Sect. 3.3.1). This interpretation is confirmed by simulation as will be shown in Fig. 11.5b. We draw an important conclusion that is not restricted to Gipps' model (and not even to traffic flow models):

> When using empirical data to assert the accuracy and predictive power of models, one has to simulate both the actual traffic dynamics *and* the process of data capture and analysis.

City traffic. Compared to the simple models of the previous chapter, the city-traffic scenario (Fig. 11.1, right column) is closer to reality as well. However, the acceleration time-series is unrealistic. By definition, there are only three values for the acceleration: Zero, a, and $-b$ (cf. Panel (e)). The resulting driving behavior is excessively "robotic" and the abrupt transitions are unrealistic.

Moreover, Gipps' model does not differentiate between comfortable and maximum deceleration: Assuming that b in Eq. (11.10) denotes the maximum deceleration, the model is accident-free but every braking maneuver is performed *very* uncomfortably with full brakes. On the other hand, when interpreting b as the comfortable deceleration and allowing for heterogeneous and/or multi-lane traffic the model possibly produces accidents if leading vehicles (which might be simulated using different parameters or even different models) brake harder than b.

In summary, Gipps' model produces good results in view of its simplicity. Modified versions of this model are used in several commercial traffic simulators. One example of such a modification is *Krauss' model* which essentially is a stochastic version of the Gipps model.

11.3 Intelligent Driver Model

The time-continuous *Intelligent Driver Model* (IDM) is probably the simplest complete and accident-free model producing realistic acceleration profiles and a plausible behavior in essentially all single-lane traffic situations.

11.3.1 Required Model Properties

As Gipps' model, the IDM is derived from a list of basic assumptions (*first-principles model*). It is characterized by the following requirements:

1. The acceleration fulfills the general conditions (11.1)–(11.5) for a complete model.
2. The equilibrium bumper-to-bumper distance to the leading vehicle is not less than a "safe distance" $s_0 + vT$ where s_0 is a minimum (bumper-to-bumper) gap, and T the (bumper-to-bumper) time gap to the leading vehicle.
3. An *braking strategy!intelligent* controls how slower vehicles (or obstacles or red traffic lights) are approached:
    - Under normal conditions, the braking maneuver is "soft", i.e., the deceleration increases gradually to a comfortable value b, and decreases smoothly to zero just before arriving at a steady-state car-following situation or coming to a complete stop.
    - In a critical situation, the deceleration exceeds the comfortable value until the danger is averted. The remaining braking maneuver (if applicable) will be continued with the regular comfortable deceleration b.
4. Transitions between different driving modes (e.g., from the acceleration to the car-following mode) are smooth. In other words, the time derivative of the acceleration function, i.e., the *jerk* J, is finite at all times.[6] This is equivalent to postulating that the acceleration function $a_{\text{mic}}(s, v, v_l)$ (or $\tilde{a}_{\text{mic}}(s, v, \Delta v)$) is continuously differentiable in all three variables. Notice that this postulate is in contrast to the action-point models such as the *Wiedemann Model* where acceleration changes are modeled as a series of discrete jumps.
5. The model should be as parsimonious as possible. Each model parameter should describe only one aspect of the driving behavior (which is favorable for model calibration). Furthermore, the parameters should correspond to an intuitive interpretation and assume plausible values.

11.3.2 Mathematical Description

The required properties are realized by the following acceleration equation:

$$\boxed{\dot{v} = a\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*(v, \Delta v)}{s}\right)^2\right] \quad \text{IDM.}} \tag{11.14}$$

[6] Typical values of a "comfortable" jerk are $|J| \leq 1.5\,\text{m/s}^3$.

The acceleration of the Intelligent Driver Model is given in the form $\tilde{a}_{\text{mic}}(s, v, \Delta v)$ and consists of two parts, one comparing the current speed v to the desired speed v_0, and one comparing the current distance s to the desired distance s^*. The desired distance

$$s^*(v, \Delta v) = s_0 + \max\left(0, vT + \frac{v\Delta v}{2\sqrt{ab}}\right) \tag{11.15}$$

has an equilibrium term $s_0 + vT$ and a *dynamical term* $v\Delta v/(2\sqrt{ab})$ that implements the "intelligent" braking strategy (see Sect. 11.3.4).[7]

11.3.3 Parameters

We can easily interpret the model parameters by considering the following three standard situations:

- When *accelerating on a free road from a standstill*, the vehicle starts with the maximum acceleration a. The acceleration decreases with increasing speed and goes to zero as the speed approaches the desired speed v_0. The exponent δ controls this reduction: The greater its value, the later the reduction of the acceleration when approaching the desired speed. The limit $\delta \to \infty$ corresponds to the acceleration profile of Gipps' model while $\delta = 1$ reproduces the overly smooth acceleration behavior of the Optimal Velocity Model (10.19).
- When *following a leading vehicle*, the distance gap is approximatively given by the *safety distance* $s_0 + vT$ already introduced in Sect. 11.3.1. The safety distance is determined by the time gap T plus the minimum distance gap s_0.
- When *approaching slower or stopped vehicles*, the deceleration usually does not exceed the comfortable deceleration b. The acceleration function is smooth during transitions between these situations.

Each parameter describes a well-defined property (Fig. 11.2). For example, transitions between highway and city traffic, can be modeled by solely changing the desired speed (Table 11.2). All other parameters can be kept constant, modeling that somebody who drives aggressively (or defensively) on a highway presumably does so in city traffic as well.

Since the IDM has no explicit reaction time and its driving behavior is given in term of a continuously differentiable acceleration function, the IDM describes more closely the characteristics of semi-automated driving by adaptive cruise control

[7] The maximum condition in Eq. (11.15) ensures that the conditions (11.1)–(11.5) for model completeness hold for all situations. Strictly speaking, this condition violates the postulate of a smooth acceleration function. However, it comes into effect only in two situations: (i) For finite speeds if the leading car is much faster, (ii) for stopped queued vehicles when the queue starts to move. The first situation may arise after a cut-in maneuver of a faster vehicle. Since $s \gg s_0$ for this case, the resulting discontinuity is small. In the second case, the maximum condition prevents an overly sluggish start and the associated discontinuous acceleration profile may even be realistic.

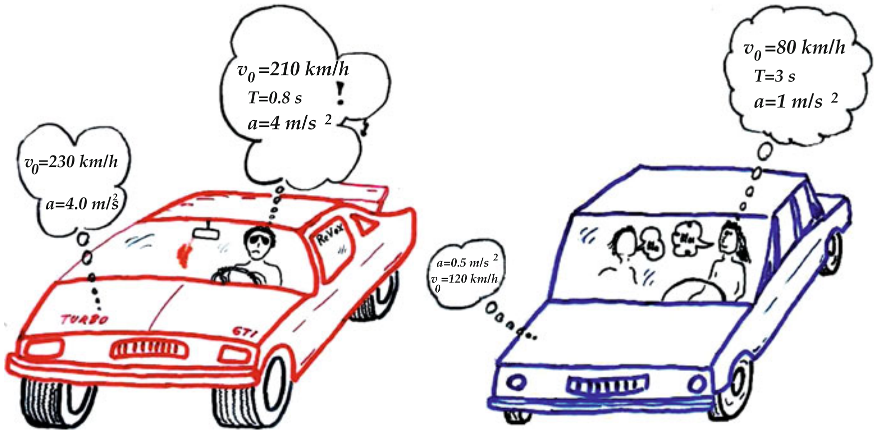

Fig. 11.2 By using intuitive model parameters like those of Gipps' model or the Intelligent Driver Model (IDM) we can easily model different aspects of the driving behavior (or physical limitations of the vehicle) with corresponding parameter values

Table 11.2 Model parameters of the Intelligent Driver Model (IDM) and typical values in different scenarios (vehicle length 5 m unless stated otherwise)

Parameter	Typical value Highway	Typical value City traffic
Desired speed v_0	120 km/h	54 km/h
Time gap T	1.0 s	1.0 s
Minimum gap s_0	2 m	2 m
Acceleration exponent δ	4	4
Acceleration a	1.0 m/s^2	1.0 m/s^2
Comfortable deceleration b	1.5 m/s^2	1.5 m/s^2

(ACC) than that of a human driver. However, it can easily be extended to capture human aspects like estimation errors, reaction times, or looking several vehicles ahead (see Chap. 12).

In contrast to the models discussed previously, the IDM explicitly distinguishes between the safe time gap T, the speed adaptation time $\tau = v_0/a$, and the reaction time T_r (zero in the IDM, nonzero in the extension described in Chap. 12). This allows us not only to reflect the conceptual difference between ACCs and human drivers in the model, but also to differentiate between more nuanced driving styles such as "sluggish, yet tailgating" (high value of $\tau = v_0/a$, low value for T) or "agile, yet safe driving" (low value of $\tau = v_0/a$, normal value for T, low value for b).[8] Furthermore, all these driving styles can be adopted independently by ACC systems (reaction time $T_r \approx 0$, original IDM), by attentive drivers (T_r

[8] Obviously, the first behavior promotes instabilities which will be confirmed by the stability analysis in Chap. 15.

comparatively small, extended IDM), and by sleepy drivers (T_r comparatively large, extended IDM).

11.3.4 Intelligent Braking Strategy

The term $v\Delta v/(2\sqrt{ab})$ in the desired distance s^* (11.15) of the IDM models the dynamical behavior when approaching the leading vehicle. The equilibrium terms $s_0 + vT$ always affect s^* due to the required continuous transitions from and to the equilibrium state. Nevertheless, to study the braking strategy itself, we will set these terms to zero, together with the free acceleration term $a[1-(v/v_0)^\delta]$ of the IDM acceleration equation. When approaching a standing vehicle or a red traffic light ($\Delta v = v$), we then find

$$\dot{v} = -a\left(\frac{s^*}{s}\right)^2 = -\frac{av^2(\Delta v)^2}{4abs^2} = -\left(\frac{v^2}{2s}\right)^2\frac{1}{b}. \tag{11.16}$$

With the *kinematic deceleration* defined as

$$b_{\text{kin}} = \frac{v^2}{2s}, \tag{11.17}$$

this part of the acceleration can be written as

$$\dot{v} = -\frac{b_{\text{kin}}^2}{b}. \tag{11.18}$$

When braking with deceleration b_{kin}, the braking distance is exactly the distance to the leading vehicle, thus b_{kin} is the minimum deceleration required for preventing a collision. With Eq. (11.18), we now understand the self-regulating braking strategy of the IDM:

- A "critical situation" is defined by b_{kin} being greater than the comfortable deceleration b. In such a situation, the actual deceleration is *even stronger* than necessary, $|\dot{v}| = b_{\text{kin}}^2/b > b_{\text{kin}}$. This overcompensation decreases b_{kin} and thus helps to "regain control" over the situation.
- In a non-critical situation ($b_{\text{kin}} < b$), the actual deceleration is less than the kinematic deceleration, $b_{\text{kin}}^2/b < b_{\text{kin}}$. Thus, b_{kin} increases in the course of time and approaches the comfortable deceleration.

Hence, the braking strategy is *dynamically self-regulating* towards a situation in which the kinematic deceleration equals the comfortable deceleration. One can show (see Problem 11.4) that this self-regulation is explicitly given by the differential equation

$$\frac{\mathrm{d}b_{\text{kin}}}{\mathrm{d}t} = \frac{v\,b_{\text{kin}}}{s\,b}\big(b - b_{\text{kin}}\big). \tag{11.19}$$

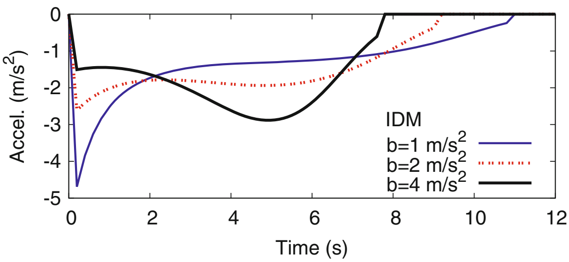

Fig. 11.3 Acceleration time-series of approaching the stop line of a *red* traffic light for different values of the comfortable deceleration. The initial speed is $v = 54$ km/h. The traffic light switches to *red* (at time $t = 0$) when the vehicle is 60 m away

Thus, the kinematic deceleration drifts towards the comfortable deceleration in *any* situation.

In the above considerations, we have ignored parts of the IDM acceleration function. To estimate their effects, the time series of Fig. 11.4e display the complete IDM dynamics when approaching an initially very distant, standing obstacle ($b_{\text{kin}} \ll b$): First, the deceleration increases towards the comfortable deceleration according to Eq. (11.19). However, due to the defensive nature of the neglected terms, the comfortable value is never realized, at least for the first vehicle. Eventually, the deceleration smoothly reduces until the vehicle stops with exactly the minimum gap s_0 left between itself and the obstacle. The following vehicles experience slightly larger decelerations than the comfortable ones, but without having to perform any emergency braking or being in danger of a collision.

Figure 11.3 shows the effects of the self-regulatory braking strategy in a situation where the vehicle is suddenly forced to stop. Drivers with $b = 1\,\text{m/s}^2$ will perceive this situation as "critical" ($b_{\text{kin}} = v^2/(2s) = 1.9\,\text{m/s}^2$) and overcompensate with even stronger deceleration. In contrast, if the comfortable deceleration is given by $b = 4\,\text{m/s}^2$, the comfortable deceleration is initially well above the kinematic deceleration and the simulated driver will brake only weakly, so that b_{kin} increases. Again, due to the other terms in the acceleration function, the actual deceleration will not reach the value of comfortable deceleration.

Why do "IDM drivers" act in a more anticipatory manner for smaller values of b? Yet why are very small values of b (less than about $1\,\text{m/s}^2$) not meaningful?

Consider the situation of approaching a standing obstacle as described above and convince yourself that the effect of the dynamical part of s^* on the acceleration prevails against all other terms. Furthermore, show that these other terms are negative in nearly all situations, thus making the driving behavior more defensive.

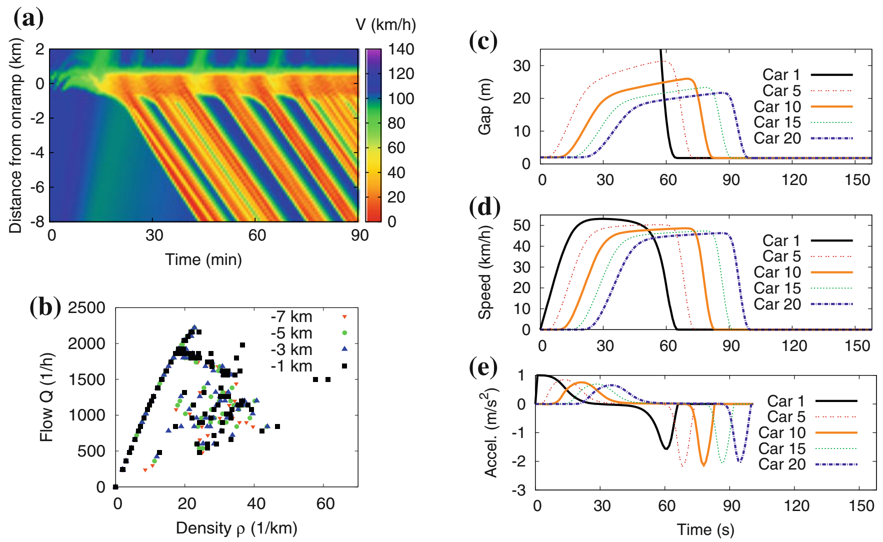

Fig. 11.4 Fact sheet of the Intelligent Driver Model (11.14). The two standard scenarios "highway" (*left*) and "city traffic" (*right*) are simulated with parameters as listed in Table 11.2. See Sect. 10.5 for a detailed description of the scenarios

11.3.5 Dynamical Properties

The *fact sheet* of the IDM, Fig. 11.4, shows IDM simulations of the two standard scenarios "traffic breakdown at a highway on-ramp" and "acceleration and stopping of a vehicle platoon in city traffic".

Highway traffic. The speed field in the highway scenario (Fig. 11.4a) exhibits dynamics similar to the one found in Gipps' model (cf. Fig. 11.1): Stationary congested traffic is found close to the bottleneck, while, further upstream, stop-and-go waves emerge and travel upstream with a velocity of approximately −15 km/h. The wavelength tends to be smaller than in real stop-and-go traffic, but the empirical spatiotemporal dynamics are otherwise reproduced very well. The growing stop-and-go waves in the simulations are caused by a collective instability called *string instability* which will be discussed in more detail in Chap. 15. As we will see in this chapter, the IDM is either unstable with respect to stop-and-go waves (string-unstable) or absolutely stable, depending on the parameters and traffic density. The model is free of accidents, however, except for very unrealistic parameters under specific circumstances.

The flow-density diagram of virtual loop detectors in Fig. 11.4b reproduces typical aspects of empirical flow-density data:

- Data points representing free traffic fall on a line, while data points from congested traffic are widely scattered.