EXPERIMENTAL CHARACTERISTICS OF TRAFFIC FLOW FOR EVALUATION OF TRAFFIC MODELLING

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Abstract: Based on recent experimental works by Kerner and Rehborn (1996a, b) new additional criteria for evaluation and validation of traffic flow models suitable for a correct simulation of experimental observed behaviors of traffic flow are proposed.

Keywords: Measurements, modelling and simulation of traffic flow, characteristic parameters of traffic flow

1. INTRODUCTION

During more than the last three decades a lot of microscopic, mesoscopic and macroscopic models for simulation of traffic flow on highways have been proposed. To validate a traffic flow model different kind of experimental characteristics of traffic have been used: average time headway, perceptional thresholds, distance headway, braking distance and other parameters characterizing the behavior of drivers following one another. Besides, the measured macroscopic characteristics of traffic flow, exactly, the velocity of traffic jams and the parameters of an average dependence of the flux on the density of vehicles, which is usually called the fundamental diagram, have often been applied to validate traffic flow models.

Nevertheless, even a correct application of these parameters for a validation of a traffic flow model and also a good correlation of the measured fundamental diagram with the fundamental diagram which is used in the model (or which is the result of the model) may not guarantee a satisfactory agreement of the results of traffic simulations with the experiment. The problem is that in the experiment traffic flow showed very complex space-time behavior which can not be satisfactory reflected enough only by the mentioned parameters and by the fundamental diagram. It is linked to the fact that besides these characteristics of traffic, different other *collective space-time effects* in traffic which cause a spontaneous appearance of diverse space-time structures can play a very important role.

Indeed, recent experimental investigations of properties of traffic jams and of a complexity in traffic flow (Kerner and Rehborn, 1996a, b) showed that this complexity is linked to space-time transitions between three qualitative different kinds of traffic: "free" traffic flow, "synchronized" traffic flow, and traffic jams. These experimental investigations allowed the conclusion that in the formation of the complexity in traffic flow a decisive role plays collective effects, in particular, effects of self-organization. These effects cause a spontaneous appearance of diverse space-time structures in traffic flow.

One of the often observed structure in traffic is a traffic jam. The term 'traffic jam' is used here and as of now for a description of the phenomenon of an appearance of a localized region of very high density of vehicles in traffic where the vehicles either cannot move at all or each of the vehicles must come to a stop (even if during a short time interval) inside the jam. The phenomenon of occurrence of traffic jams is of great importance in traffic. Therefore for a lot of purposes in traffic modelling and simulation it is necessary to use a traffic flow model which is able to reproduce the properties of *real* traffic jams. In this article the consideration of criteria for evaluation and validation of traffic flow models will be restricted by those criteria which follow both from experimental properties of traffic jams and from the correlation of parameters of traffic jams with the parameters of the free traffic flow, i.e., of the flow where vehicles are able to change a lane and to pass.

The article is organized as following. In sect. 2 the main experimental results of the investigations of macroscopic properties of traffic jams (Kerner and Rehborn, 1996a, b) will be considered briefly. In sect. 3 the additional criteria for evaluation and validation of traffic flow models suitable for a correct simulation of experimental observed behaviors of traffic flow will be formulated. In sect. 4 based on a qualitative theoretical analysis of properties of traffic jams, the characteristic parameters of traffic flow will be discussed.

2. MACROSCOPIC EXPERIMENTAL CHARACTERISTICS OF TRAFFIC JAMS

The phenomenon of phantom traffic jam without obvious reason met almost every driver. At first, drivers could move with a relatively high speed on a road. Then, drivers suddenly find themselves in a region with a very high density of vehicles, where they could not move at all. After some time, drivers could move again at a high speed, but to their great surprise, nothing had happened on the road which could have caused the traffic jam. Therefore, one can have the conclusion that a traffic jam is a localized pattern of large amplitude of the density in traffic flow. Treiterer (1975) was the first who has found out that a traffic jam which moved upstream could really spontaneously occur without obvious reason in traffic flow. Besides, Treiterer (1975) has discovered that an occurrence of the jam has been accompanied by a hysteresis phenomenon. The latter may indicate that the occurrence of a jam is a nonlinear phenomenon.

Recently Kerner and Rehborn (1996a, b) have discovered qualitatively new properties of jams. They have investigated macroscopic properties of 'wide' traffic jams, i.e., jams whose widths are considerably larger than the widths of both upstream and downstream jam's fronts, where the density and the average speed of vehicles sharply spatially change. It has been found out that when parameters of traffic (road conditions, number of lanes, percentage of long vehicles, etc.) are given and no hindrances for traffic exist in the outflow from the jam, then (Kerner and Rehborn, 1996a, b):

1. Wide traffic jams can move through a highway for a long time keeping their form and main parameters.
2. The stable localized complex structure consisting of a few traffic jams can exist on the highway.
3. The downstream fronts of different wide jams are nearly the same stationary moving structure. It means that the mean values of the parameters of the downstream front of wide jams are nearly the same for different wide jams. The parameters of the downstream front under consideration are: the velocity of this front, the flux out from the jam, the density of vehicles inside the jam, the average speed and the density of vehicles in the outflow from the jam. These parameters remain almost constant in the course of time.
4. An almost stationary moving traffic jam can exist on the highway.
5. The flux in free traffic flow can be considerably higher than the flux out from a wide jam.
6. The development of jams whose widths monotonously increase in the course of time show a tendency to the self-organization of the downstream front of the jam to the stationary moving structure noticed in item 3.

The properties 1-4 are illustrated in Figs. 1 and 2, the property 5 in Fig. 3 and the property 6 in Fig. 4. The case which is shown in Fig. 1 has two peculiarities. First, the localized structure of two wide jams following one another has been observed. These two jams could move through the highway about 50 min staying qualitative the same (Fig. 1). Second, the flux into the second (downstream) jam equaled to the flux out from the first (upstream) jam during some time, when the both jams were between the intersections I2 and I3, where no on- and off-ramps existed on the highway. It turned that the mean value of the flux out from both jams approximately equaled one another. For this reason, the second jam was a nearly stationary moving one.

The downstream fronts of the both jams were nearly the same stationary moving structures. Therefore, these fronts are represented in Fig. 3 by the line J with the coordinates $(\overline{\rho}_{min}, \overline{q}_{out})$ and $(\overline{\rho}_{max}, 0)$ which has its slope equal to the mean value of the velocity of the front $\overline{v}_g \approx -15$ km/h. Here $\overline{q}_{out}$ is the mean value of the flux out from the second jam; $\overline{\rho}_{min}$ is the mean value of the density in the outflow from this jam; $\overline{\rho}_{max}$ is the mean value of the density inside the jam. One can see from Fig. 3 that the flux $\overline{q}_{out}$ is considerably lower than the maximal flux in free traffic flow $q^{(free)}_{max}$ (Fig. 3). The same conclusions can be made from Fig. 4, where the development of a jam is shown. It can be seen that the downstream front of the jam (points 6-7-8 in Fig. 4(d)) shows a tendency to the self-organization into a stationary moving structure which as well as in Fig. 3 is represented in Fig. 4(d) by the line J. Note that in contrary to Fig. 3, in Fig. 4 the experimental data only for the left lane have been used. It explains the differences between the values $\overline{q}_{out}$, $\overline{\rho}_{min}$, $\overline{\rho}_{max}$ in Figs. 3 and 4 if it is taken into account that the percentage of long vehicles on the left lane was negligible in comparison to the right lane of the highway.

3. ADDITIONAL CRITERIA FOR EVALUATION OF TRAFFIC FLOW MODELS

As it follows from the presented experimental results, there are the *characteristic parameters* of traffic flow which do not depend on the initial conditions in traffic flow. These characteristic parameters are:

- The flux out from a wide traffic jam q_{out}.
- The velocity of the downstream front of a wide traffic jam v_g.
- The average speed of vehicles in the outflow from a wide traffic jam v_{max}.
- The density of vehicles inside traffic jam ρ_{max}.

For example the characteristic parameters of traffic flow do not depend on the flux and on the density of vehicles in free traffic flow as well as on the length of a road. The characteristic parameters of traffic flow depend only on the parameters of traffic, i.e. for example, on the weather, on other road conditions, on the existence of hindrances for traffic in the outflow from a jam and on the car's technology.

Besides the characteristic parameters of traffic flow, there are other important demands for traffic modelling which follow from the experimental

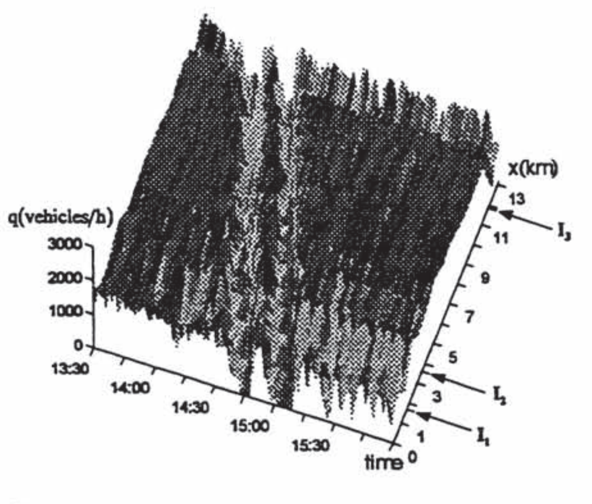

Fig. 1. The results of the experimental investigations of wide jams taken from Kerner and Rehborn (1996a): The propagation of jams on September 10, 1992 through the section of the highway A5 in Germany which has 16 set of detectors. On the distance-axis the arrangement of the intersections with other highways (I1, I2 and I3) are shown.

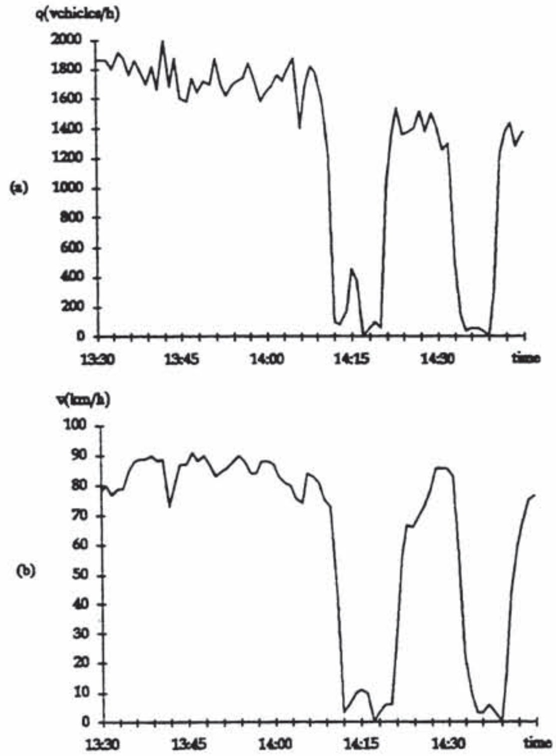

Fig. 2. The experimental flux (a) corresponding to jams shown in Fig. 1 and the average speed of vehicles (b) averaged over all lanes of the highway from the set of detectors D9 which is situated at 7.2 km.

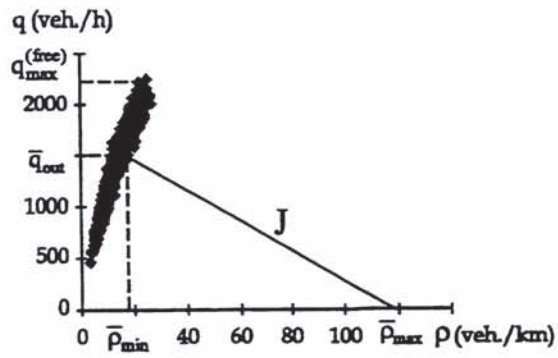

Fig. 3. A representation of the downstream front of the second jam shown in Figs. 1 and 2 (line J) and the experimental data (black quadrates) during the time when traffic was free from any traffic jams (Kerner and Rehborn, 1996a). The experimental points correspond to the averaging the experimental data over all lanes of the highways.

results of investigations of traffic jams (Kerner and Rehborn, 1996a, b):

- After a wide jam has been formed, the characteristic parameters of traffic flow which calculate a traffic flow model should not depend on the flux of vehicles into the jam.
- The maximal possible flux in free traffic flow $q_{max}^{(free)}$ which shows a traffic flow model in general should not be correlated to the flux out

from a wide traffic jam q_{out}. The flux q_{out} has to be considerably lower than $q_{max}^{(free)}$ (Fig. 3).

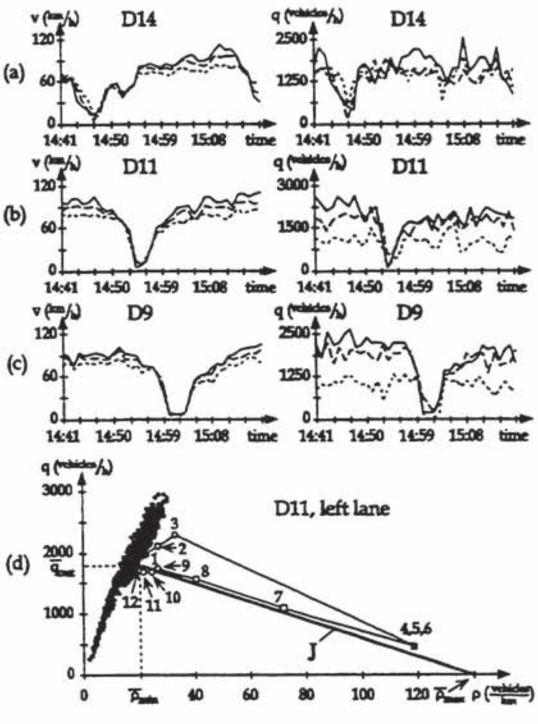

Fig. 4. The development of a jam (August 25, 1995) whose width monotonously increases in time (Kerner and Rehborn, 1996b): (a) - (c) The kinetics of traffic jams development. (d) The representation of the free flow (black points) and of the jam (points 1-12) on the flux-density plane (the detector D11, left lane).

- Besides a single traffic jam, a traffic flow model should reproduce a stable *complex localized structure* consisting of a few traffic jams. In particular, such a localized structure can consist exceptionally of wide jams. In this case if the distance between wide jams is considerably larger than the lengths of their fronts, the downstream jams should be almost stationary moving structures. It means that their parameters do not change in time.

Note that the existence of the characteristics parameters of traffic flow, which do not depend on the initial conditions in traffic, has first been predicted and theoretical investigated by Kerner and Konhäuser (1994). They have made this conclusion based on a theoretical analysis of a macroscopic traffic flow model (Kerner and Konhäuser, 1993). Therefore the latter traffic flow model is able to reproduce the characteristic parameters of real traffic flow. It has been confirmed by a comparison of the results of a theory of traffic jams developed by Kerner and Konhäuser (1994) with the experiment (Kerner and Rehborn, 1996a). The same conclusion can also been made from recent results of investigations of a new method for a determination of section-related traffic data on the basis of a traffic flow simulation based on the mentioned macroscopic traffic flow model which has recently been developed by Kronjäger, *et al.* (1995).

4. EXPLANATION OF PROPERTIES OF TRAFFIC JAMS

In this section a qualitative theoretical analysis of the properties of traffic jams in traffic flow will be made. This analysis helps to explain the characteristic parameters of traffic flow.

4.1. Flux of vehicles out from traffic jam

Suppose that a road is long enough and an initial state of traffic flow on this road is a homogeneous one. Let us designate the average speed, the density and the flux of vehicles in this homogeneous state as v_h, ρ_h and q_h, correspondingly. Obviously, $q_h = \rho_h v_h$. Let us further propose that due to a growth of a *localized* perturbation in traffic which has spontaneously occurred in traffic flow a wide jam has been formed. Owing to the localized character of the perturbation the jam upstream and downstream is surrounded by the same initially homogeneous traffic flow where the flux of vehicles is q_h. Therefore in the case under consideration the flux of vehicles which flows *into* this jam q_{in} equals to the flux in the initial flow, i.e., $q_{in} = q_h$.

Concerning the flux of vehicles out from the jam q_{out} some general suppositions may be made. It may be expected that the mean value of this flux does not change in the course of time. This supposition can be explained by the following. Each driver standing inside the jam can start to escape from the jam after two conditions have been fulfilled: (i) The driver in front of him has already escaped the jam, exactly, he has begun to move away from the jam. (ii) Due to the latter moving, after some time the distance between the both drivers has exceeded some "safety distance". In other words, there is an average finite delay time τ_{del} between two following drivers escaping from the jam. Note that a process of the moving of the downstream front of the jam occurs due to the escape of drivers from the jam. Because the average distance between vehicles standing inside the jam including an average length of each vehicle equals to $1/\rho_{max}$, the velocity of the downstream front of the jam is:

$$v_g = -\frac{1}{\rho_{max}\tau_{del}}. \quad (1)$$

It has been proposed that the flux inside the jam is zero. Therefore, the velocity of the downstream front of the jam is connected to the flux out from the jam correspondingly to the obvious formula:

$$v_g = -\frac{q_{out}}{\rho_{max} - \rho_{min}}. \quad (2)$$

The formulas (1) and (2) allow to write the flux out from the jam in the form:

$$q_{out} = \frac{1}{\tau_{del}}\left(1 - \frac{\rho_{min}}{\rho_{max}}\right) \approx \frac{1}{\tau_{del}}. \quad (3)$$

The approximation which has been made on the right hand side of (3) is permitted because the ratio $\rho_{min}/\rho_{max} << 1$. At given parameters of traffic the mean value of the delay time τ_{del} is a constant value. Therefore, under the condition that τ_{del} is the constant, the flux out from the jam (3) is also a constant value.

4.2. Boundary flux of jam's existence

To understand the characteristic parameters of traffic flow, note that a traffic jam can exist for a long time only if the flux of vehicles into the jam q_{in} either equals or is higher than the flux out from the jam q_{out}:

$$q_{in} \geq q_{out}. \quad (4)$$

Indeed, if the flux of vehicles out from the jam q_{out} is higher than the flux into the jam q_{in}, i.e., if

$$q_{in} < q_{out}, \quad (5)$$

then the whole number of vehicles stored in the traffic jam gradually would decrease in the course of time. As a result, the width of the jam L_s would also decrease. As a consequence, the jam would disappear. Already from the conditions (4) and (5) two important conclusions about properties of jams may be made (Kerner and Konhäuser, 1994): (i) The boundary flux of the jam's existence $q_h = q_b$, at which a traffic jam either can still exist or can be excited in this flow, equals to the flux out from the traffic jam q_{out}:

$$q_b = q_{out}. \quad (6)$$

(ii) The maximal possible flux in the free traffic flow $q_{max}^{(free)}$ can considerably exceed the boundary flux of the jam's existence q_b:

$$q_{max}^{(free)} > q_b. \quad (7)$$

The condition (6) follows from (4) and (5). Indeed, if the flux of vehicles in an initial homogeneous flow q_h which equals to the flux into the jam $q_h = q_{in}$ is higher than q_{out}, then correspondingly to (4) the jam can exist in traffic flow. If in contrary the flux in the initial homogeneous flow q_h is lower than q_{out} then correspondingly to (5) the jam gradually disappears. Therefore, the value of the flux in the initial homogeneous flow $q_h = q_b$ which satisfies to the condition (6) is really the boundary flux of the jam's existence. In other words, if the flux in the initial homogeneous flow $q_h < q_b$, the flux of vehicles which flows into the jam is lower than the flux which flows out from the jam. In the latter case a jam cannot be excited independently from the amplitude of a time-limited localized perturbation in an initially homogeneous traffic flow.

To understand the condition (7), note that the critical amplitude of a localized perturbation which is necessary for an excitation of a traffic jam in an initially homogeneous traffic flow is maximal in the critical point $q_h = q_b$. Indeed, a localized perturbation in traffic flow can grow only if the flux of vehicles into a region of higher density inside this perturbation is higher than the flux which flows out from this region. However, at $q_h = q_b$ as it follows from (6) the flux into the jam exactly equals to the flux out from the jam. Therefore the initial perturbation should already have the same amplitude, as well as the jam has, to excite this jam in the initially homogeneous flow. For this reason when the flux q_h just slightly exceeds the value q_b only the localized perturbations of very high amplitude may grow in traffic flow. In other words, there should be a wide range of the fluxes, $q_b < q_h < q_{max}^{(free)}$, where an initially homogeneous state of traffic flow can exist. The latter confirms the condition (7).

4.3. Local cluster of vehicles in traffic flow

Let us consider the form of a localized structure -a *local cluster of vehicles* which is self-formed in an initial homogeneous traffic flow with the flux $q_h > q_b$ due to the growth of an initial localized perturbation of this flow. First it can be concluded that correspondingly to the conditions (6) and $q_h > q_b$, the flux out from the jam q_{out} is lower than the flux in the initial homogeneous flow q_h. Therefore a transition layer between a state of traffic flow with the flux q_{out} which is self-formed by the jam downstream from the jam and the initial homogeneous flow with the flux q_h is formed. This transition layer moves downstream. Second, owing to the condition $q_h > q_b$ more and more vehicles are stored inside the jam in the course of time, i.e., the width of the jam L_s should monotonously increase in time. Therefore the local cluster of vehicles which appears in traffic flow consists of three parts (Fig. 5) (Kerner and Konhäuser, 1994):

1. The proper traffic jam with the density of vehicles ρ_{max} moving upstream.
2. The new almost homogeneous traffic flow with the flux q_{out} which is formed by the jam downstream.
3. The transition layer between this new traffic flow $(\rho_{min}, q_{out}, v_{max})$ and the initially homogeneous traffic flow (ρ_h, q_h, v_h) moving downstream.

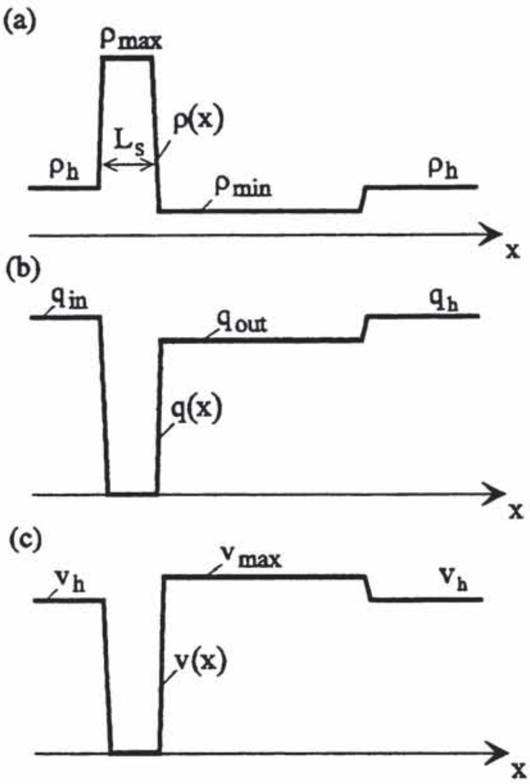

Fig. 5. Distributions of the density (a), of the flux (b) and of the average speed of vehicles (c) in a local cluster of vehicles.

Because the delay time τ_{del} between some two consequent escapes of drivers from a wide jam is a constant value in the average, the new traffic flow with the flux q_{out} which is formed by the jam downstream is almost homogeneous. This flow is also stable, because correspondingly to the formula (6) the flux in this flow equals to the boundary flux of the jam's existence. For these reasons, the downstream front of wide jams is a stationary moving structure. This structure is exceptionally formed by the jam. For this reason the parameters of the downstream front of wide jams do not depend on the initial conditions. The latter influences only the flux into the jam, i.e., on the width of the jam. This explains the characteristic parameters of wide traffic jams. In its turn the characteristic parameters of traffic jams determine very important characteristics of traffic flow, in particular, the boundary flux of traffic jam existence (see (6)). It also explains why these parameters are the characteristic parameters of traffic flow.

5. CONCLUSIONS

Let us suppose a traffic flow model shows a fundamental diagram related to experimental observations and also reproduces a process of a local self-organization in traffic flow which leads to a formation of traffic jams moving upstream. Even these properties of the model are not enough to show the real features of traffic jams. In addition, the traffic flow model should reproduce both the characteristic parameters of traffic flow and other demands for traffic flow modelling which have been formulated in sect. 3. Only in this case it may be expected that the model can correctly reproduce the macroscopic properties of real traffic jams. Therefore, the mentioned characteristic parameters and properties of traffic flow may be considered as additional criteria for evaluation of traffic flow modelling and simulation.

However, even these relatively difficult additional demands for traffic modelling are not enough for a modelling of the whole picture of complexity of nonlinear phenomena observed in traffic flow. In particular, the latter conclusion follows from a consideration of the macroscopic properties of the complexity of traffic flow which have recently been discovered by Kerner and Rehborn (1996b).

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