PHYSICAL REVIEW E

STATISTICAL PHYSICS, PLASMAS, FLUIDS,
AND RELATED INTERDISCIPLINARY TOPICS

THIRD SERIES, VOLUME 53, NUMBER 2 FEBRUARY 1996

RAPID COMMUNICATIONS

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Experimental features and characteristics of traffic jams

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(Received 3 November 1995)

Based on experimental investigations of traffic on highways it is shown that traffic jams can move stable through a highway keeping their structure and characteristic parameters for a long time (at least for about 50 min, when the jams moved through the longest, 13.1 km, section of the investigated highways). The experimental features of an almost stationary moving jam have been found. An occurrence of complex space-time structures of traffic inside a wide traffic jam has been observed.

PACS number(s): 05.40.+j, 47.54.+r, 89.40.+k

I. INTRODUCTION

Numerous experimental investigations of traffic have been made to understand phenomena in traffic flow (e.g. [1,2]). It has been found that traffic flow of low density is laminar flow. However, from many observations and, in particular, from the investigations of vehicle trajectories in traffic made by Treiterer in 1975 [1], it has experimentally been found that when the density is increased moving upstream traffic jams can spontaneously be formed in traffic flow.

Recent investigations of different traffic flow models have shown a transition from an initially homogeneous traffic flow to a jammed state [3]. The theoretical analysis of traffic jams which has been made in [4] has shown that important parameters of traffic jams (the velocity of a jam, the density and the flux of vehicles in the outflow from the jam) are intrinsic characteristics of traffic flow. These characteristic features of traffic jams also play an important role for other properties of traffic [4].

In recent years a lot of induction loop detectors have been installed on many German highways. They are situated along the highway at distances 0.4–1.2 km from one another. This makes it possible to follow traffic jams during a relatively long time with appropriate accuracy of measured parameters of traffic. In this Rapid Communication, based on measured parameters of traffic, characteristic features of traffic jams will be found.

II. PROPERTIES OF TRAFFIC JAMS

Different moving traffic jams on the highways A3 (between Leverkusen and Köln), A43 (between Bochum and Recklinghausen), and A5 (between Frankfurt and Bad Homburg) in Germany, which have been determined on different days in 1991–1995, have been investigated. In this Rapid

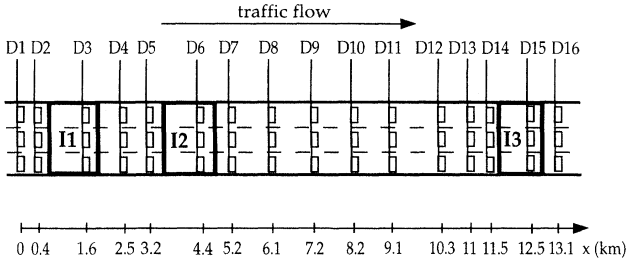

FIG. 1. Schematic configuration of the highway A5 between Frankfurt and Bad Homburg in Germany. On the x axis the coordinates of the corresponding detectors D1, . . . ,D16 are shown.

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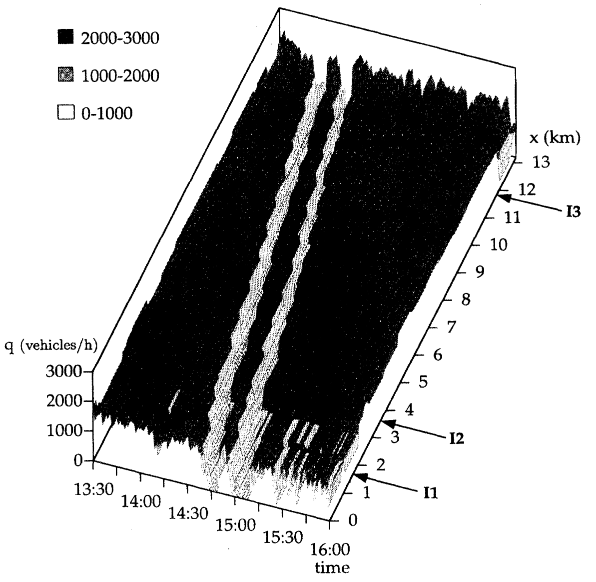

FIG. 2. The propagation of the traffic jams through the highway A5 between Frankfurt and Bad Homburg in Germany on Friday, September 10, 1992: the averaged flux of vehicles $q(x,t)$. For a better visual demonstration the flux $q(x,t)$ is shown here as continuous along the x axis. In the reality this flux corresponds to the interpolation of the measured discrete fluxes $q(x_i,t)$ at the sets of the detectors Di, $i=1,\ldots,16$, situated at the discrete points x_i (Fig. 1). In their turn, the fluxes $q(x_i,t)$ have here been averaged over all lanes of the road.

Communication we restrict our consideration to only one case, when a propagation of traffic jams through the 13.1 km long section of the highway A5 on Friday, September 10, 1992, has been observed. It allows one to show characteristic properties of traffic jams which have been found in different cases.

The section of the highway A5 consists of a three-lane road [except a short part (0.4 km) left to the intersection I1], which has three intersections (I1, "Westkreuz Frankfurt"; I2, "Nordwestkreuz Frankfurt"; and I3, "Bad Homburger Kreuz") with other highways, correspondingly (Fig. 1). There are 16 sets of induction loop detectors (D1, . . . , D16) on this section. The sets of detectors D1, D2, D4, D5, D7–D14, and D16 are situated on the road (Fig. 1). The set of the detectors D4, D5, D7–D14, and D16 consists of three detectors for a left (passing) lane, a middle lane, and a right lane, correspondingly. The other sets of detectors are situated inside the intersections: D3 in the intersection I1, D6 in the intersection I2, and D15 in the intersection I3 (Fig. 1).

An induction loop detector records a vehicle crossing the detector and measures its speed. A local road computer produces two sequences of pulses for each lane of the road separately: (i) for the average flux corresponding to the number of vehicles which have crossed a detector during the one minute interval; (ii) for the average speed corresponding to the arithmetic mean quality of speeds of vehicles crossing the detector during the same time interval.

On Friday, September 10, 1992, two traffic jams, which propagated during about 50 min together through the whole section of the highway under consideration, have been observed (Fig. 2). Although these two traffic jams met three intersections I1, I2, and I3, where vehicles both exited and entered the road, the structure of both traffic jams did not change significantly; they could move stable through all the intersections.

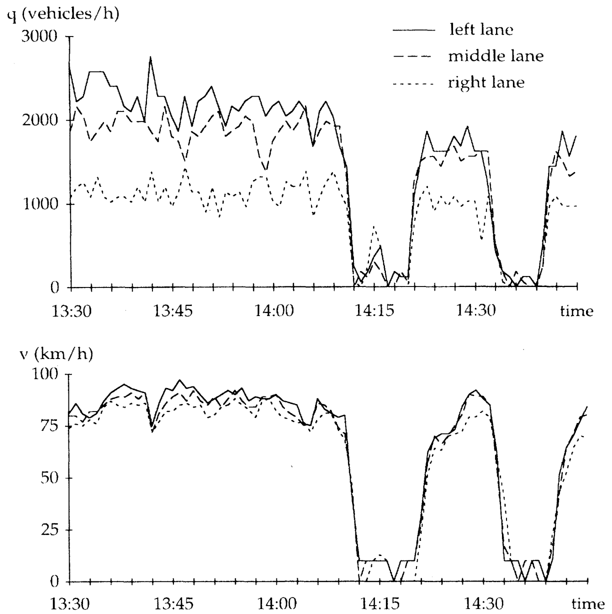

FIG. 3. The experimental fluxes and the average experimental speed of vehicles shown separately for each lane of the highway from the sets of detectors D9 which are situated at $x_9=7.2$ km (Fig. 1).

Note that in the case under consideration the on- and off-ramps are situated on the road only in the vicinities of the intersections I1, I2, and I3 (Fig. 1). For an investigation of parameters of traffic jams in "pure conditions," i.e., when the traffic jams were not upon the influence of on- and off-ramps and other inhomogeneities of the road, such as intersections with other roads, it seems especially interesting to examine the propagation of the traffic jams through the part of the road between the intersections I2 and I3 in more detail. Indeed, this part is about 7 km long and it has 8 sets of detectors (D7–D14, Fig. 1).

The typical dependencies of the fluxes and the average speed of vehicles on time for each lane in this part of the road are shown in Fig. 3. As can be expected, the flux and the average speed of vehicles on the left (passing) lane are noticeably higher than for the right lane both upstream and downstream from the traffic jams (Fig. 3). When vehicles reach one of two traffic jams they should slow down nearly to a standstill (Fig. 3). The moments of time, when the drivers reaching the jam should sharply slow down up to a standstill, were not exactly the same for the different lanes, especially with regard to the left jam. However, the maximal spreading of these moments of time was in the order of magnitude of the interval of the averaging of the flow and of the speed of vehicles (1 min).

The investigated traffic situation (Fig. 2) had at least two peculiarities: (i) the traffic jams could move through the highway during about 50 min but their structure was staying qualitatively the same; (ii) the localized structure in traffic flow, which consisted of two jams following one another, had been observed. We will refer to the left (upstream) and the right (downstream) traffic jam in this localized structure shown in Figs. 2 and 3 as the first jam and the second jam, correspondingly. The peculiarity (ii) may seem like an additional difficulty for the investigation of the characteristic features of jams in traffic flow. It has, in reality, the important advantage that although the parameters of traffic had obviously been changed in the course of time, the parameters of the right (downstream) jam did not change between the intersections I2 and I3 (Fig. 1) essentially. Therefore, this jam was on the average almost a *stationary* moving structure in traffic.

To understand the latter circumstance notice that there is an essential difference between the reason of an appearance and of deviations in time of the fluxes into the first and into the second traffic jam. Indeed, the flux of vehicles into the first jam $q_{\text{in }1}(t)$ was determined by "free" traffic which came from both the highway A5 upstream from the detector D1 and traffic which exited to off-ramps and traffic which entered to on-ramps in the intersections I1 and I2. On the contrary, the flux into the second jam $q_{\text{in }2}(t)$ at $t<14{:}30$, i.e., until the downstream front of the first jam had reached the intersection I2, was determined only by vehicles which left the first traffic jam. Indeed, there was no other source of vehicles which could reach the second traffic jam at $14{:}15<t<14{:}30$. In other words, the flux into the second jam $q_{\text{in }2}(t)$ was entirely determined by the flux out from the first jam $q_{\text{out }1}(t)$. For this reason, as it followed from the experimental data, the mean (over the time) values of these fluxes were

$$\bar{q}_{\text{out }1} \approx \bar{q}_{\text{in }2}, \tag{1}$$

where $\bar{q}_{\text{in }2} \approx 1500$ veh./h; $\bar{q} = (1/7)\Sigma_{i=8}^{14}\bar{q}|_i$, $\bar{q}|_i = (1/3)(\bar{q}_{\text{left}} + \bar{q}_{\text{middle}} + \bar{q}_{\text{right}})|_i$, where i is the number of the set of the detectors, and the indexes "left," "middle," and "right" correspond to the left, the middle, and the right lanes of the road. The dispersion of the mean values of the flux out from the traffic jams for different sets of the detectors D8–D14 was within the accuracy of the detectors.

Note that the flux out from the first jam $q_{\text{out }1}(t)$ corresponds to the rate of the escaping vehicles from almost a standstill in the jam. The same process determines the flux out from the second jam $q_{\text{out }2}(t)$. Apparently for this reason the experimental data showed that both the mean value of the flux out from the first jam $\bar{q}_{\text{out }1}$ and the mean value of the flux out from the second jam $\bar{q}_{\text{out }2}$ were approximately the same:

$$\bar{q}_{\text{out}} = \bar{q}_{\text{out }2} \approx \bar{q}_{\text{out }1}, \tag{2}$$

i.e., as it follows from (1),

$$\bar{q}_{\text{out}} \approx \bar{q}_{\text{in }2}. \tag{3}$$

In spite of a possible lane changing in traffic, the formula (2) was approximately valid for each lane separately: $q_{\text{out 1, left}} \approx \bar{q}_{\text{out 2, left}}$, and so on. The found values were as follows: $\bar{q}_{\text{out 2, left}} \approx 1800$ veh./h, $\bar{q}_{\text{out 2, middle}} \approx 1600$ veh./h (within the accuracy of the measurements), and $\bar{q}_{\text{out 2, right}} \approx 1100$ veh./h (within 15%) [5].

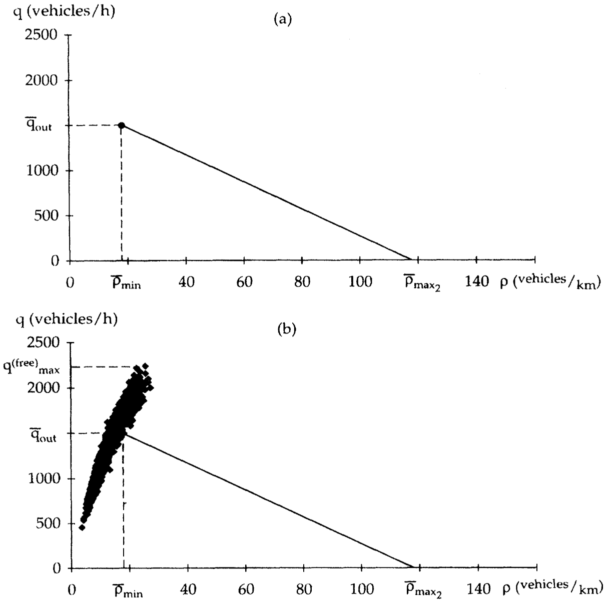

FIG. 4. A comparison of the experimental characteristics of the stationary moving traffic jam with the predictions of the theory: (a) the representation of the downstream front of the second traffic jam on the (ρ,q) phase plane; (b) the concatenation of the experimental data averaged over three lanes of the highway (black quadrates) taken from the detectors D9–D14 during the time $7{:}00<t<13{:}45$, when traffic was free from any jams, with the experimental characteristic features of the jam. The solid line in (b) is the same as in (a)

The average velocities of the fronts of the traffic jams can be estimated from the experimental data by the obvious formula $\bar{v}_g = L_{\text{Di-Dj}}/T_{\text{Di-Dj}}$ where $T_{\text{Di-Dj}}$ is the average time interval between two moments of the appearance of the corresponding front of the traffic jam at the detector Di and the detector Dj; $L_{\text{Di-Dj}}$ is the distance between these detectors. The average over all the pair of detectors D8–D14 velocities of the second jam's fronts corresponding to the experimental data were

$$\bar{v}_{g2} = \bar{v}_{gr2} \approx \bar{v}_{g12}, \tag{4}$$

$\bar{v}_{g2} \approx -15$ km/h. This value is in a good agreement with the earlier experimental result which was found by Treiterer in 1975 in the U.S.A. [1].

The experimental data also made it possible to estimate the average density of vehicles downstream from the second jam. The mean speed of vehicles [averaged as well as the flux (1)] directly downstream from the jam was $\bar{v}_{\text{out }2} \approx 84$ km/h. This means that the mean density directly downstream from the jam approximately equaled $\bar{\rho}_{\text{min}} = \bar{q}_{\text{out}}/\bar{v}_{\text{out }2} \approx 18$ veh./km. The mean value of the speed and the density directly downstream from the jam for each lane were as follows: $\bar{v}_{\text{out 2, left}} \approx 89$ km/h, $\bar{v}_{\text{out 2, middle}} \approx 84$ km/h, $\bar{v}_{\text{out 2, right}} \approx 79$ km/h, $\bar{\rho}_{\text{min, left}} = \bar{q}_{\text{out 2, left}}/\bar{v}_{\text{out 2, left}} \approx 20$ veh./km, $\bar{\rho}_{\text{min, middle}} \approx 19$ veh./km, and $\bar{\rho}_{\text{min, right}} \approx 14$ veh./km [5].

Therefore, the experimental data showed that the existence of the first jam on the road had maintained an almost stationary state of the moving second traffic jam downstream, the mean parameters of which almost did not change with regard to time. This stationary moving traffic jam existed until the downstream front of the first jam had reached the intersection I2 (Fig. 1), i.e., as long as the flux into the second jam was entirely determined by the flux out from the first jam. Afterwards, at $t > 14{:}30$, the second jam became a nonstationary one. However, the parameters $\bar{v}_{gr\ 2}, \bar{q}_{\rm out}, \bar{\rho}_{\rm min}$ did not change.

The experimental results presented are in good agreement with the conclusions of a theory of traffic jams [4]. Using the results of this theory, in addition, the average density of vehicles inside of the second traffic jam (Fig. 3) can be estimated. With this purpose, the downstream front of this jam has been approximated on the (ρ,q) phase plane as the line which has its slope equal to the velocity of the jam $\bar{v}_{g2}$ and the coordinates $(\bar{\rho}_{\rm min}, \bar{q}_{\rm out})$ and $(\bar{\rho}_{\rm max\ 2}, 0)$[Fig. 4(a)]. By using the values determined above we find that $\bar{\rho}_{\rm max\ 2} = \bar{q}_{\rm out}/|\bar{v}_{g2}| + \rho_{\rm min} \approx 118$ veh./km. The densities inside the jam for each lane were as follows: $\bar{\rho}_{\rm max\ 2,\ left} \approx 140$ veh./km, $\bar{\rho}_{\rm max\ 2,\ middle} \approx 126$ veh./km, and $\bar{\rho}_{\rm max\ 2,\ right} \approx 87$ veh./km [5].

After the experimental data for the period of time, when traffic was free from any jams, on this (ρ,q) phase plane had been inserted [Fig. 4(b)], we have found out that the flux out from the jam, which corresponding to the theory [4] equals the boundary flux (the threshold) for traffic jam existence, was considerably lower than the maximal flux $q_{\rm max}^{\rm (free)}$ in laminar ("free") traffic flow [$q_{\rm max}^{\rm (free)}/\bar{q}_{\rm out} \approx 1.5$ Fig. 4(b)]. Therefore, the maximal capacity of a highway can considerably exceed the threshold of an occurrence of jams in traffic flow.

Considering the characteristics of the traffic jams we did not take into account that inside traffic jams was a complex space-time structure of the flux: the flux of vehicles could be changed from zero (a standstill) to some values, then it could become zero once more, and so on a few times during the duration of the jam for a fixed observer (Fig. 3). This effect was especially noticeable for the first traffic jam, where the flux inside the jam increased up to 600 veh./h per lane. A form of this changing of the flux inside the traffic jam, corresponding to the experimental data from different sets of detectors, did not seem to be periodical with regard to time and space.

Apparently, this effect could be linked to the following. When drivers suddenly met a traffic jam, they had to slow down very sharply up to a standstill. As a result, the "blanks" between vehicles inside the traffic jam could be very different from one pair of vehicles to the others. After some time, some of the drivers inside the traffic jam might begin to reduce the largest "blanks." As a result, new blanks appeared upstream from these drivers. This could give rise to drivers upstream covering the latter blanks, and so on. In this case the moving upstream blanks between vehicles inside the traffic jam could be created. This might explain the complex space-time character of the flux inside traffic jams.

III. CONCLUSIONS

The experimental data showed the following.

(i) Traffic jams can move through a highway for a long time while keeping their form and main parameters. The stable localized complex structure of traffic jams can exist on the highway.

(ii) The mean values of the fluxes out from different wide jams approximately equal one another. The downstream fronts of different wide jams are nearly the same stationary moving structure which mean characteristics (velocity, etc.) remain almost constants in the course of time. These conclusions are valid if both parameters of traffic (road conditions, number of lanes, percentage of long vehicles, etc.) are held nearly constant and no hindrance for traffic exists in the outflow from the jams.

(iii) The almost stationary moving traffic jam can exist on the highway.

(iv) The flux and the density in laminar traffic flow can be considerably higher than the flux out from the jam and the density directly downstream from the jam, correspondingly.

(v) Complex space-time structures of traffic inside a wide traffic jam can appear.

ACKNOWLEDGMENTS

Our thanks are to H. Kirschfink, P. Konhäuser, T. Scheiderer, and U. Uerlings for fruitful discussions and to the Autobahnamt Frankfurt for help in the preparation of the experimental data.

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[1] J. Treiterer, Ohio State University Technical Report No. PB 246 094, Columbus, Ohio, 1975 (unpublished).

[2] W. Leutzbach, *Introduction to the Theory of Traffic Flow* (Springer-Verlag, Berlin, 1988); M. Koshi, M. Iwasaki and I. Ohkura in *Proc. 8th Intl. Symp. on Transp. and Traffic Theory*, edited by V. F. Hurdle *et al.* (Elsevier, Amsterdam, 1983), pp. 403–426; F. L. Hall, L. A. Brian, and M. A. Gunter, Transp. Res. A **20**, 197 (1986).

[3] O. Biham, A. A. Middleton, and D. Levine, Phys. Rev. A **46**, 6124 (1992); K. Nagel and M. Schreckenberg, J. Phys. (France) I **2**, 2221 (1992); T. Nagatani, Phys. Rev. E **48**, 3290 (1993); B. S. Kerner and P. Konhäuser, *ibid.* **48**, 2335 (1993); M. Bando, K. Hasebe, A. Nakayama, A. Shibata, and Y. Sugiyama, *ibid.* **51**, 1035 (1995); K. Nagel and M. Paczuski, *ibid.* **51**, 2909 (1995); M. Schreckenberg, A. Schadschneider, K. Nagel, and N. Ito *ibid.* **51**, 2939 (1995).

[4] B. S. Kerner and P. Konhäuser, Phys. Rev. E **50**, 54 (1994).

[5] To understand the differences between the latter values, notice that for the case under consideration the mean shares of long vehicles on the left, the middle, and the right lanes were approximately 1%, 10%, and 40%, correspondingly.