

Traffic-like collective movement of ants on trails: absence of jammed phase

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We report some counterintuitive experimental results on unidirectional traffic-like collective movement of ants on trails. Our work is primarily motivated by fundamental questions on the collective spatio-temporal organization in systems interacting motile constituents driven far from equilibrium. Making use of the analogies with vehicular traffic, we analyze our experimental data for the spatio-temporal organisation of the ants on the trail. From this analysis, we extract the flow-density relation as well as the distributions of (a) velocities of the ants and (b) distance-headways. Some of our observations are consistent with our earlier models of ant-traffic, which are appropriate extensions of the totally asymmetric simple exclusion process. However, the most interesting and, perhaps, counterintuitive result is that, in sharp contrast to highway traffic, the average velocity of the ants is almost independent of their density on the trail. Consequently, no jammed phase is observed.

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Ants form large trail systems [1] which share many features of vehicular transportation networks. Emergence of the trail pattern has received some attention in the literature [1–3]. Single trails are often stable for hours or days and can be considered the analogs of highways. Therefore, the collective movement of ants on trails (from now onwards, referred to as “ant-traffic”) is analogous to vehicular traffic on highway networks [4, 5]. The social behavior of ants also indicates the possibility that biological evolution has optimized ant-traffic. Surprisingly, despite its striking similarities with vehicular traffic, the *collective* properties of ant-traffic have not been studied experimentally until recent years.

The pioneering experiments on ant-traffic [6] and all the subsequent related works [7–11] used bidirectional trails where the nature of flow is dominated by the head-on encounters of the ants coming from opposite directions [7, 8, 11]. But, in vehicular traffic, where flow in opposite directions are normally well separated and head-on collisions can occur only accidentally, the spatio-temporal organization of the vehicles in each direction is determined by the interactions of the vehicles moving in the same direction. Therefore, in order to investigate the similarities and differences between vehicular traffic and ant-traffic, we have collected and analyzed data on *unidirectional* traffic of ants on a natural trail using methods adapted from traffic engineering [12–14].

All the experimental data reported here have been collected on a natural trail of monomorphic ant species *Leptogenys processionalis* [3, 15]. This choice ensured that all the ants have the same body size and exhibit identical behavioral responses. Moreover, we maintained the natural situation so that the true features of ant-traffic could be captured by our video recordings. Furthermore, we focussed on a particular section of the trail which had nei-

ther crossings nor branching which would be the analogs of ramps in vehicular traffic [13, 14]. Thus, being far from nest and the food as well as from intersections, this segment mimics an effectively infinite linear trail [4, 16]. The shape of the observed section of the trail remained unaltered for several hours and, therefore, we collected each data set continuously for about 13 minutes. We have verified that during this time the flow can be considered to be stationary and is not disturbed by external factors. Finally, we compared the data recorded at ten different trails of the same type and found that our conclusions drawn from these are generic (at least, for the traffic of the ant species used in our studies) [17].

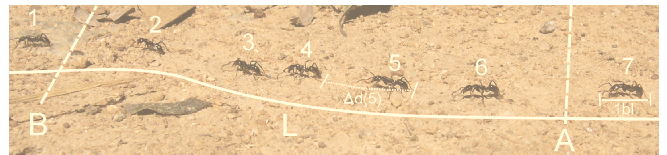


FIG. 1: A snapshot of the observed trail section. Although it exhibits some curvature its length can easily be estimated in units of the body-length of one single ant ($1bl \approx 18mm$).

One of the distinct behavioral characteristics of individual ants in the ant-traffic is the absence of overtaking. Although some ants (temporarily) left the trail and were passed by succeeding ones, we never observed any ant speeding up in order to overtake some other ant in front. We exploited this observation to develop a convenient method for our data analysis which we’ll explain below.

The actual length L of the observed section of the trail between the two points marked A and B in Fig. 1 has been estimated by averaging over the paths of individual

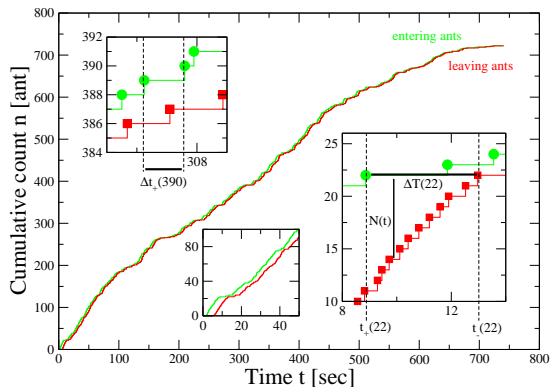


FIG. 2: Figure illustrating the technique employed for data extraction. The cumulative count of the ants which have entered $n_+(t)$ (\bullet) and left $n_-(t)$ (\square) the trail section between A and B. The right inset shows the travel time ΔT for the 22th ant. On the left inset the time-headway Δt_+ of the 390th ant is shown.

ants which passed through this section. Putting equi-spaced marks on a transparency mounted on the video screen, we obtained $L = 17$ bl, in the units of the body-length (bl) of a single ant, where $1 \text{ bl} \approx 18 \text{ mm}$ for the ant species *Leptogenys processionalis* used in our study.

Since no overtaking takes place, ants can be uniquely identified by the ordered sequence in which they enter the observed section of the trail, i.e. they follow a FIFO-principle (first-in-first-out). Suppose, the n -th ant enters the section at A at time $t_+(n)$ and leaves the section at B at time $t_-(n)$. An efficient tool for analyzing such data is the *cumulative plot* (Fig. 2) ([12]); it shows the numbers $n_+(t)$ and $n_-(t)$ of ants which have passed the point A and B, respectively, up to time t . The two resulting curves, which are sometimes called *arrival function* and *departure function* can be obtained by inverting $t_+(n)$ and $t_-(n)$, respectively.

This allows us to extract basic data in a very efficient way [26]. The travel time $\Delta T(n)$ of the n -th ant in the section between the points A and B is given by

$$\Delta T(n) = t_-(n) - t_+(n) \quad (1)$$

and the *time-averaged* speed of the n -th ant during the period $\Delta T(n)$ is given by

$$v(n) = \frac{L}{\Delta T(n)} \quad (2)$$

The time-headway of two succeeding ants can be obtained easily at the entrance and exit points A and B (Fig. 2, left inset). Since $v(n)$ is, by definition (eqn.(2)), the time-averaged velocity $v(n)$ of the n -th ant, the distance-headway between the n -th ant and the ant in front of it is given by

$$\begin{aligned} \Delta d(n) &= \Delta t_+(n) v(n-1), \\ \Delta t_+(n) &= t_+(n) - t_+(n-1). \end{aligned} \quad (3)$$

Entry and exit of each ant changes the instantaneous number $N(t)$ of the ants in the trail section between A and B by one unit (Fig. 2, right inset). Therefore $N(t)$ fluctuates, but stays constant in between two events of entry or exit. Sorting the counts of these events by time one obtains a chronological list $\{t_i\} = \{t_{\pm}(n)\}$ of the changes of the instantaneous particle number

$$N(t) = n_+(t) - n_-(t) = \text{const.} \quad \text{while } t \in [t_i, t_{i+1}[. \quad (4)$$

In order to estimate the local density which is experienced by the n -th ant during the time interval $\Delta T(n)$ it spends within the observed trail section we first determine the average number of ants in the same section during the time interval $\Delta T(n)$:

$$\langle N \rangle_{t(n)} = \frac{1}{\Delta T(n)} \sum_{t_i=t_+(n)}^{t_i < t_-(n)} N(t_i)(t_{i+1} - t_i) \quad (5)$$

The (dimensionless) density $\rho(n)$ affecting the movement of the n -th ant is given by

$$\rho(n) = \frac{\langle N \rangle_{t(n)}}{N_{\max}} = \frac{\tilde{\rho}(n)}{\tilde{\rho}_{\max}} \quad \text{with } \tilde{\rho}(n) = \frac{\langle N \rangle_{t(n)}}{L}, \quad (6)$$

where $N_{\max} = 17 = L/(1 \text{ bl})$ and $\tilde{\rho}_{\max} = N_{\max}/L$. Our empirical data for ρ are in the interval $[0, 0.8]$. Thus, the instantaneous particle numbers and the single-ant velocity are averaged over the same time-interval $\Delta T(n)$.

The average velocity of the ants is plotted against the corresponding density in fig. 3; the resulting flow-density relation, which is called *fundamental diagram* in traffic engineering [4, 13], is plotted in the inset of the fig. 3. The most unusual feature of the data shown is that, unlike vehicular traffic, there is no significant decrease of the average velocity with increasing density [4, 13, 14]. Consequently, the flux obtained by the hydrodynamic equation increases approximately linearly over the entire regime of observed density. The jammed branch of the fundamental diagram, which is commonly observed in vehicular traffic and which is characterized by a monotonic decrease of flow with increasing density, is completely missing in the fundamental diagram of ant-traffic shown in fig. 3. Obviously effects of mutual blocking, which are normally expected to become dominant at high densities [4, 13, 14], are strongly suppressed in ant-traffic.

From the time-series of the single-ant velocities we have also determined their distributions in different density regimes (Fig. 4). The most striking feature is that the distribution becomes much sharper with increasing global density whereas the most probable velocity decreases only slightly.

Another important quantity that characterizes the spatial distribution of the ants on the trail is the distance-headway distribution. The time-series (Fig. 5 top left), obtained by using (3), shows clustering of small distance-headways whereas larger headways are much more scattered. The distribution of these headways (see Fig. 5)

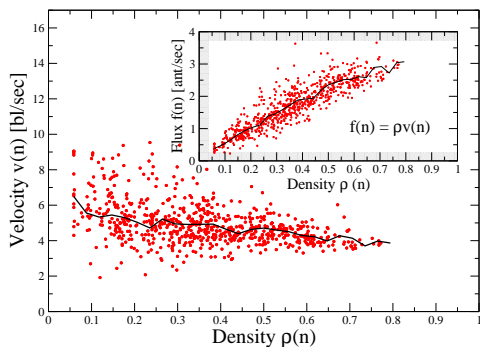


FIG. 3: Average velocity (solid line) and single-ant velocities (dots) for unidirectional single-lane trail section of length $L = 17$ bl. The corresponding flux-velocity relation, the so-called *fundamental diagram* is plotted in the inset. Mutual blocking is obviously suppressed as the average velocity is almost independent of the density. Consequently, the flux increases almost linearly with the density in the fundamental diagram (see inset).

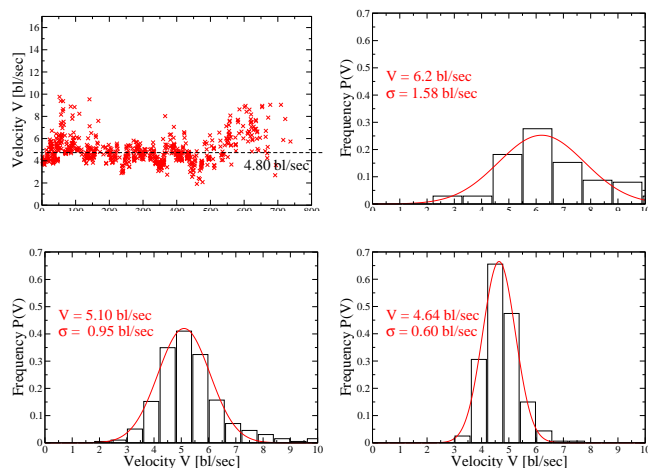


FIG. 4: The velocities of the individual ants are plotted as function of time. In the remaining three figures, the velocity distributions of the ants for small ($\rho(n) \in [0, 0.2]$), intermediate ($\rho(n) \in [0.2, 0.4]$) and large ($\rho(n) \in [0.4, 0.8]$) densities have been shown. For all regimes the corresponding Gaussian $P(v) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-(v - V)^2/(2\sigma^2))$ is also shown.

becomes much sharper with increasing density while the maximum shifts only slightly to smaller headways. At low densities, predominantly large distance-headways are found; the corresponding distribution for sufficiently long distance-headways is well described by a negative-exponential distribution which is characteristic of the so-called random-headway state [13]. In contrast, at very high densities mostly very short distance-headways are found; in this regime, the log-normal distribution appears to provide the best fit to our empirical data.

The absence of a jammed phase in the fundamental diagram is closely related to the characteristic features

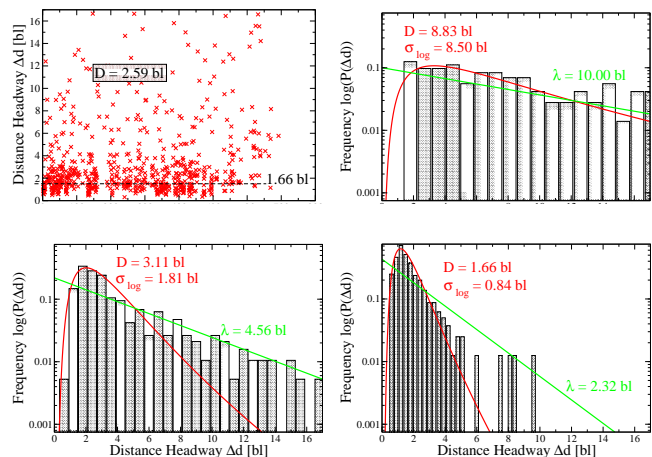


FIG. 5: Distance-headways vs. time show a clustering of short distances thereby indicating the existence of a density independent intra-platoon separation between the ants. The remaining three figures show the distance-headway distributions for small ($\rho(n) \in [0, 0.2]$), intermediate ($\rho(n) \in [0.2, 0.4]$) and large ($\rho(n) \in [0.4, 0.8]$) densities. Depending on the density regime a log-normal $P(\Delta d) = \frac{1}{\Delta d \sigma_{\log} \sqrt{2\pi}} \exp(-(\Delta d - \log(\Delta d))^2/(2\sigma_{\log}^2))$ or negative-exponential $P(\Delta d) = \exp(-\Delta d/\lambda)$ distribution applies.

of the distributions of the distance-headways of the ants along the observed section of the trail. The dominant, and directly observable, feature of this spatial distribution is the platoons formed by the ants. Ants inside a platoon move with almost identical velocities maintaining small distance-headways. These intra-platoon distance-headways are responsible for the clustering of data observed in the corresponding time-series Fig. 5. In contrast, larger distance-headways are inter-platoon distances. The full distribution of distance-headways has an average of $D = 2.59$ bl which is quite close to the value $D = 1.66$ bl found for very high densities. This indicates the existence of a density-independent distance-headway for the ants moving inside platoons. Formation of these platoons has been demonstrated by our earlier simple models of ant-traffic [18–22] which are appropriate extensions of the totally asymmetric simple exclusion process [16].

The interpretations of the observed trends of variations of the flux, average velocity and distance-headway distribution with increasing density is consistent with the corresponding variation of the distribution of the velocities of the ants (Fig. 4). Ants within a platoon move at a slower average velocity whereas solitary ants can move faster if they detect a strong pheromone trace created by a preceding platoon. Moreover, since fluctuations of velocities of different platoons are larger than the intra-platoon fluctuations, the distribution becomes sharper at higher densities because the platoons merge thereby reducing their number and increasing the length

of the longest one. As can be seen in Fig. 4 the maximum of the velocity distribution is almost independent of the density. Its position at sufficiently large densities can be interpreted as platoon velocity, $v_p \approx 4.6$ bl/s.

In this letter, we have reported results of our empirical studies of unidirectional ant-traffic on a natural ant trail. Remarkably, we have not observed any event of overtaking of one ant by another. Instead, we have observed formation of platoons which we observed earlier in our simple models of ant-traffic under various conditions [18–22]. The most counter intuitive fact, which has emerged from our empirical investigations, is that in ant-traffic (at least for the ant species and the trail systems used in our studies), flow increases monotonically with the density of the ants. In other words, unlike vehicular traffic, no jammed branch is exhibited by the flow-density relation for ant-traffic.

It is worth pointing out that physical origin of the occurrence of the nearly constant average velocity of the vehicles in highway traffic is very different from the constant velocity of ants in ant-traffic. In vehicular traffic, the average velocity of the vehicles remains practically unaffected by increasing density, provided the density is sufficiently low, because at those densities the vehicles are well separated from each other and, therefore,

can move practically unhindered in the so-called free-flow state. On the other hand, in ant-traffic, this constant velocity regime is a reflection of the fact that ants march together collectively forming platoons which reduce the effective density. We have also not found any evidence for phenomena like hysteresis, synchronised flow, etc. which have been reported for vehicular traffic [4, 14]. Although platoon formation is considered to be relevant also for synchronized flow [14], there is no characteristic velocity of these platoons, in contrast to the case of ant traffic.

Thus, in spite of some superficial similarities, the characteristic features of ant-traffic seems to be very different from those of vehicular traffic. Perhaps, ant-traffic is analogous to human pedestrian traffic [10, 11, 23], as was conjectured beautifully by Hölldobler and Wilson in their classic book [1]; in a future work, we intend to explore this analogy empirically and by quantitative modeling. Our results may have important implications for swarm intelligence [24] and ant-based computer algorithms [25].

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