Supplementary Note

1. Materials and methods

Camphor and glycerol were purchased from Wako Chemicals (Kyoto, Japan). Water was first distilled and then purified with a Millipore Milli-Q filtering system (pH of the obtained water: 6.3, resistance: > 20 MΩ). A camphor disk (diameter: 3 mm, thickness: 1 mm, mass: 5 mg) was prepared using a pellet die set for FTIR. A plastic boat was made by cutting a polyester film (thickness: 0.1 mm) into a discoid shape (diameter: 6 mm), and a camphor disk (diameter: 3 mm, thickness: 1 mm, a typical mass: 2 mg) were stuck on one edge of the plastic disk with an adhesive [Fig. 1(a)]. A glass container with a circular route was filled with water or glycerol aqueous solution of 5 or 10 mM (depth of water phase: 5 mm, width: 10 mm, inner diameter: 145 mm). The movement of the camphor boat was monitored with a digital video camera (SONY DCR-VX700, minimum time-resolution: 1/30 sec) in an air-conditioned room at 298±2 K, and then analyzed by an image-processing system (ImageJ 1.41, National Institute of Health, USA).
2. Explanation of ‘cluster mode’

We propose a novel inanimate system composed of camphor boats in an annular water channel. The experimental setup is illustrated in Fig. S1 (same as Fig. 1 in the manuscript).

![Illustration of experimental setup](image)

**FIG. S1 Illustration of experimental setup.** (a) Design of the camphor boat. A plastic boat was made by cutting a polyester film into a discoid shape, and a camphor disk were stuck on one edge of the plastic disk with an adhesive. (b) The boats were floated on a glass container with a circular route filled with water or glycerol aqueous solution of 5 or 10 mM. (c) Illustration of the interaction between the camphor boats through the camphor layer. The driving force of following boat decreases due to the camphor layer developed from the first boat.

From an appropriate condition that each boat affects two or more of the following boats due to excessive decay length, ‘clusters’ of boats were observed in both the experimental results and the numerical calculation (Fig. S2b,c). In contrast to the congestion flow system, the first boat of the cluster did not accelerate, and thus the boats moved in a group. Therefore, no shock waves were observed, even though the distribution of the boats was inhomogeneous.

The cluster formation depends on the condition that the first boat is slower than the following boats. This particular condition can be explained not by the characteristics of the first boat, but by the sigmoidal relation between $\gamma(c)$ and $c(x,t)$ (Fig. S2a). In the case of excessive decay length of the camphor layer, the camphor concentration increases at the following boat. When the concentration around the following boats reaches at the inflection point of the sigmoidal function, the driving force of the
following boat can become faster than that of the first boats, even though the difference in camphor concentration of constant. As a result, a slow first boat induces the cluster mode.

FIG. S2 Experimental results and phenomenological explanation of ‘Cluster’ mode. (a) Illustration of phenomenological scenario to explain the ‘cluster’ formation. (b) Snapshot and c, space-time diagram of ‘cluster’ mode.
3. Mathematical analysis

We introduced a mathematical model for the collective motion of camphor boats in a narrow circular chamber. This model is based on the Nagayama model. The motion of the \(i\)-th boat is assumed to be expressed by the following Newtonian equation.

\[
m \frac{\partial^2 x_i}{\partial t^2} = -\mu \frac{\partial c_i}{\partial t} + \left[ \gamma(c(x_i + L, t)) - \gamma(c(x_i, t)) \right]. \tag{1}
\]

The surface tension \(\gamma(c)\) is assumed to be expressed as a sigmoidal function of the surface concentration of the camphor molecular layer \(c(x, t)\) as obtained from experimental results. In this model, we assume

\[
\gamma(c) = \frac{1}{2} \left[ \gamma_{\text{water}} - \gamma_{\text{camphor}} \right] \tanh\left( \left( c - c_{\text{threshold}} \right) + 1 \right) + \gamma_{\text{camphor}}. \tag{2}
\]

The surface concentration of the camphor molecular layer \(c(x, t)\) is assumed to obey the reaction-diffusion equation, as follows:

\[
\frac{\partial c(x, t)}{\partial t} = D \frac{\partial^2 c(x, t)}{\partial x^2} - k_0 c(x, t) + \alpha \sum_{i=1}^{N} \delta(x_i - x). \tag{3}
\]

Here we show that the present theoretical model corresponds, in a certain condition, to the optimal velocity model (OV model) to describe the traffic on highway. First, we assume that the relaxation time of \(c(x, t)\) in (1) is sufficiently shorter than the time needed for each boat, in its migration process, to experience definite change of the camphor concentration of surrounding solution. Then, quasi–steady–state approximation of (1);

\[
0 = D \frac{\partial^2 c(x, t)}{\partial x^2} - k_0 c(x, t) + \alpha \delta(x_i - x) \tag{A1}
\]

holds. The solution of (A1);

\[
c_{qi}(x, t) = \sum_{i=1}^{N} c_i \exp\left( \frac{-|x - x_i|}{\mu} \right) \tag{A2}
\]
is a superposition of those obtained from the contribution of each $x_i$, where $c_0 = \frac{\alpha}{2} \sqrt{\frac{1}{Dk_0}}$ is camper concentration at the rear edge of boat (for the isolated boat system), and $\mu = \frac{D}{\sqrt{k_0}}$ is the correlation length between boats through camphor field.

If $\mu$ is sufficiently shorter than the interval between contiguous boats, $c_{\text{steady}}(x)$ at the rear and front edges of boat $i$ is dominantly influenced by the neighboring boats, that is,

$$c_{qs}(x_i + L, t) = c_0 \exp\left(-\frac{|x_{i+1} - (x_i + L)|}{\mu}\right) + c_0 \exp\left(-\frac{|x_{i+1} - (x_i + L)|}{\mu}\right) + c_0 \exp\left(-\frac{L}{\mu}\right)$$

(A3)

$$c_{qs}(x_i, t) = c_0 \exp\left(-\frac{|x_{i+1} - x_i|}{\mu}\right) + c_0 \exp\left(-\frac{|x_{i+1} - x_i|}{\mu}\right) + c_0$$

(A4)

Assuming, in addition, that $\mu$ is close to or shorter than $L$, the 2nd terms in the r.h.s. of (A3) is neglected like;

$$c_{qs}(x_i + L, t) \approx c_0 \exp\left(-\frac{|x_{i+1} - (x_i + L)|}{\mu}\right) + c_0 \exp\left(-\frac{L}{\mu}\right) = \hat{c}(x_{i+1} - x_i - L, t)$$

and that $c_0 \geq c_{\text{threshold}}$ holds which means $\gamma(c_{qs}(x_i, t)) \approx \gamma_{\text{camphor}}$, then, equation (1) has the form;

$$m \frac{\partial^2}{\partial t^2} x_i = -\mu \frac{\partial x_i}{\partial t} + \frac{1}{2} \gamma_{\text{water}} - \gamma_{\text{camphor}} \left(\tanh\left(-\left(\hat{c}(x_{i+1} - x_i - L, t) - c_{\text{threshold}}\right)\right) + 1\right)$$

(A5)

This is just a typical form of OV-model which has a qualitative fit to the data widely extracted from highway traffic.