Critical Density of Experimental Traffic Jam

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Abstract In a previous experiment, we have demonstrated that a traffic jam emerges without any bottleneck at a certain high density. In the present work, we performed an indoor circuit experiment in Nagoya Dome and estimated the critical density. The circuit is large (314 m in circumference) compared to the previous experiment. Positions of cars were observed in 0.16 m resolution. We performed 19 sessions by changing the number of cars from 10 to 40. We found that jammed flow was realized in high density while free flow in low density. We also found the indication of metastability at an intermediate density. The critical density is estimated by analyzing the density-flow relation. The critical density locates between 0.08 and 0.09 m^{-1}. It is consistent with that observed in real expressways.

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1 Introduction

Traffic jams are familiar daily phenomena observed on expressways and city streets. Even from naive observations, traffic flow can be divided into two types: smooth flow, which occurs under light traffic and in which cars run almost at the allowed maximum speed; and jammed flow, which occurs under heavy traffic. In jammed flow, jam clusters, in which cars stop or move slowly, emerge and propagate upstream.

Fundamental diagrams describing the density-flow relation are widely used for analyzing traffic flow. Observations of real expressway traffic show that fundamental diagrams (e.g. Fig. 1) have two regions divided by a certain density value: free (smooth) flow with low density, and jammed flow with high density. In low density traffic, cars run at an almost constant speed, and therefore the flow increases in proportion to the density. The flow and the average speed for high density traffic, on the other hand, decrease with the density. The data points from high density traffic are broadly scattered; i.e. the speed and density fluctuate widely in jammed flow due to the existence of jam clusters.

Since the 1990s, many researchers have studied traffic flow from a physics point of view and various theoretical models for traffic flow have been proposed and studied extensively [1–6]. Those approaches have clarified that a homogeneous flow becomes unstable, leading to a traffic jam, if the density exceeds a critical value. Therefore the emergence of traffic jams is understood as a dynamical phase transition controlled by the density of cars.

In a previous study, we performed a traffic jam experiment using real cars on an outdoor circuit of 230 circumference in order to verify the theoretical understanding of traffic jams as a dynamical phase transition [7, 8]. In the study, we demonstrated

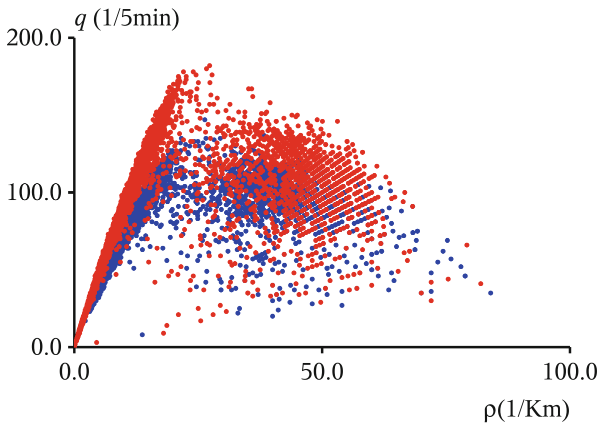

Fig. 1 Fundamental diagram observed on a Japanese highway. *Red* points are taken from the fast lane and *blue* ones from the slow lane

that traffic jams emerge at a certain high density without bottlenecks. And we observed the metastable homogeneous flow that appears as a precursor to traffic jams.

An experimental investigation of the density dependence of flow is required for confirming that the emergence of traffic jams is a really dynamical phase transition. For this purpose, we performed an extended experiment with varying number of cars under an improved environment [9]. The experiment was conducted on a circuit set in the Nagoya Dome, an indoor baseball field [10]. The new circuit was larger (314 m in circumference) than that used in the previous experiment. And we employed a laser scanner for higher-resolution positioning of the cars. We intend to estimate the critical density by comparing observations in real highways. To this end, we study the fundamental diagrams from the experimental data.

2 The Experiment

In order to study the effects of car density on traffic flow, inhomogeneity in the circuit should be reduced as low as possible, as it may act as bottlenecks. Therefore we needed to use a circular road on flat ground with homogeneous conditions. For accessing a flat, concrete floor of the Nagoya Dome, the pitching mound and artificial turf were removed and areas around the bases were covered with gray sheets in order to reduce visual inhomogeneity (Fig. 2). On a circuit of 314 m circumference, we were able to vary the density of cars by $10^{-2}\,\mathrm{m}^{-1}$.

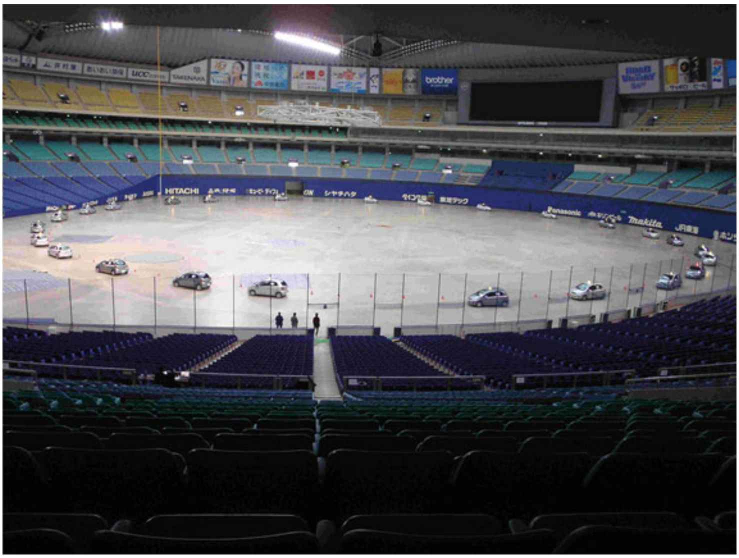

Fig. 2 Bird's-eye view of 50 m radius (314 m circumference) circuit in the Nagoya Dome. The field is flattened by removing the pitching mound and artificial turf

In the previous experiment, we read car positions manually from video data captured by a 360° camera; the positioning error in this case was roughly ±0.5 m. In this experiment, we employed a laser scanner (Sick LD-LRS 1000) located at the center of the circuit to measure car positions with an improved resolution. The scanner rotated at a frequency of 5 Hz, detecting the distance to objects every 360°/1,920°; the resulting time resolution was 10^{-4} s, and the spatial resolution was 0.16 m at a distance of 50 m. The stream of data was stored in a computer connected to the scanner, allowing sequences of position and speed for each car to be reconstructed. The details of the data acquisition and the spacetime diagrams are given in Ref. [9].

We conducted 19 sessions. For each session, the number of cars are varied from 10 to 40. All of cars were of the same model and specifications (Toyota Vitz: 1.3L, 3885m long, automatic transmission). We use data from 14 sessions for analyses.

3 Fundamental Diagrams and Estimating the Critical Density

We examined the fundamental diagrams which represent the density-flow relation. On real expressways, induction-loop coils are buried beneath observational points on a road and count the cars passing by the point and measure their speed. The number of cars q and their average speed v are recorded, for example, every 5 min. Then the density ρ at a given point and time is calculated from the relation $q = \rho v$.

To obtain a fundamental diagram from the experimental data, we place three virtual observational points, which are spaced at intervals of 120° for collecting a sufficient number of data. At each observational point, we count the number of cars passing and average their speed by intervals of 45 s, the duration determined based on the time needed for a jam cluster to move around the circuit.

Figure 3 shows the fundamental diagram for all sessions except two sessions which exhibited stop-and-go motions. This fundamental diagram is similar to that

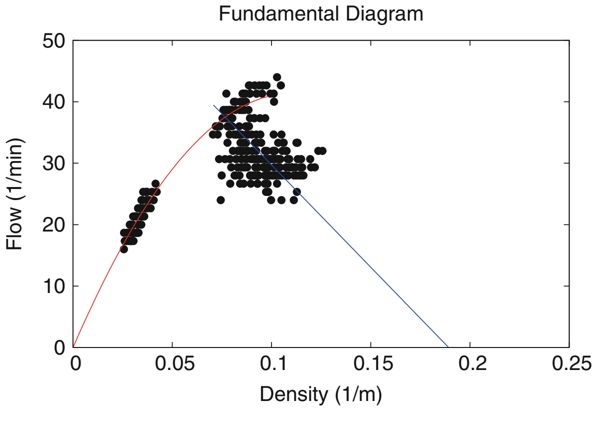

Fig. 3 Fundamental diagram for the selected sessions excluding two sessions with stop-and-go traffic. The *red curve* and the *blue line* are drawn as references to show the typical behavior of free and jammed flows

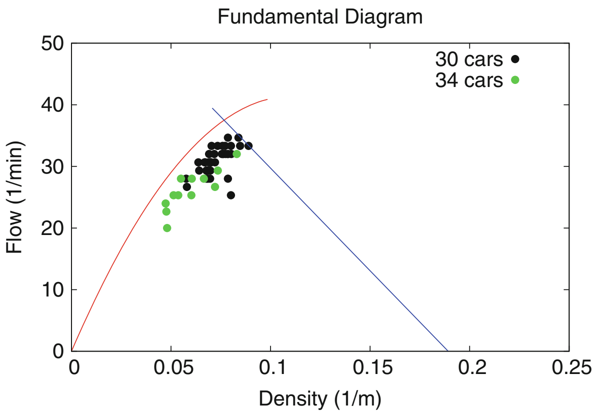

Fig. 4 Fundamental diagram for the selected sessions with stop-and-go traffic

extracted from traffic on real expressways. In Fig. 3 we find three typical features: free flow, jammed flow and metastable states. The red curve and the blue line in Fig. 3 are drawn as references to show the typical behavior of free and jammed flows, respectively.

Data points from the sessions with small numbers of cars, $10 \leq N \leq 25$, locate in the vicinity of the red curve. Here, the flow is an increasing function of the density, which is a typical feature of free flow. For the sessions with large numbers of cars, $N \geq 32$, data points are scattered broadly near the blue line. The flow shows the typical feature of jammed flow. Data points from the sessions with intermediate number of cars, $N = 28$ and 30, distribute around both the red curve and the blue line. This shows the typical feature of metastable states. Thus, we can conclude that critical density locates between $0.08\,\text{m}^{-1}$ $(N = 25)$ and $0.09\,\text{m}^{-1}$ $(N = 28)$.

The fundamental diagram for the two sessions that exhibited stop-and-go traffic, in which cars stop or nearly stop in jam clusters, is shown in Fig. 4. Because cars are detected only when they pass by the observation point, stopped cars are not taken into account in the flow measurement and in the average speed. In other word, the fundamental diagram consists mainly of data from cars moving smoothly outside of jam clusters. Because the speeds of cars outside the jam cluster are nearly the same as those in free flow, the diagram resembles that for a free flow. It can be seen that the average speed is a bit smaller and the amplitude of fluctuation is larger than those in a 'true' free flow because the motions of cars catching up with and escaping from the jam clusters are also included in the data. The resemblance between stop-and-go traffic and free flow has been reported also for the fundamental diagram of a real expressway traffic [11].

4 Summary and Discussions

We conducted the experiment to confirm that the emergence of a traffic jam is a dynamical phase transition controlled by the density of cars. And we estimated the critical density based on the experimental data. In our previous study [7, 8], which was conducted on an outdoor field, we demonstrated that a traffic jam occurs at a certain high density without bottlenecks. The current experiment was carried out on an indoor circuit of 314 m circumference with high resolution measurements (i.e. 0.2 s in time and 0.16 m in space). For estimating the critical density, the number of cars was varied from 10 to 40 [9]. Based on our analysis of fundamental diagrams, we confirmed that a dynamical phase transition between free and jammed flow occurs at a critical density. We also observed that metastable states occur at intermediate densities between free and jammed flows. The critical density was estimated to locate between 0.08 and 0.09 m^{-1}.

We can compare the critical density obtained in this study with that measured on a real expressway. The critical density of an expressway in which the observed average speed is 120 $\mathrm{km\,h}^{-1}$ in free flow is known to be 0.025 m^{-1} (25 cars km^{-1}) [7]. In our present experiment, on the contrary, the average speed in free flow was about 40 $\mathrm{km\,h}^{-1}$. Suppose a car requires a headway that is three times larger when driving three times faster, our measured experimental critical density is consistent with values observed on the expressway.

In this paper, we discussed the phase transition based on conventional observables, such as fundamental diagrams, measured in real expressways. And we did not mention any models, because we intended to estimate the critical density by comparing with observations in real expressways without depending on any models.

We showed that the transition between free and jammed flow occurs at a critical density and metastable states appear around the critical density. In this sense, the transition seems to be first order. However, it is different from phase transitions of ordinary equilibrium systems. In a traffic flow, particles (cars) in the system are moving, and emerged patterns (jam clusters) also move. Therefore the transition is essentially dynamical.

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References

1. D.E. Wolf, M. Schreckenberg, A. Bachem (eds.), *Workshop on Traffic and Granular Flow* (World Scientific, Singapore, 1996)
2. M. Fukui, Y. Sugiyama, M. Schreckenberg, D.E. Wolf (eds.), *Traffic and Granular Flow'01* (Springer, Berlin, 2003)
3. D. Chowdhury, L. Santen, A. Schadschneider, Phys. Rep. **329**(4–6), 199 (2000)
4. D. Helbing, Rev. Mod. Phys. **73**(4), 1067 (2001)
5. T. Nagatani, Rep. Prog. Phys. **65**(9), 1331 (2002)
6. B.S. Kerner, *The Physics of Traffic* (Springer, Berlin, 2004)
7. Y. Sugiyama, M. Fukui, M. Kikuchi, K. Hasebe, A. Nakayama, K. Nishinari, S. Tadaki, S. Yukawa, New J. Phys. **10**(3), 033001 (2008)

8. A. Nakayama, M. Fukui, M. Kikuchi, K. Hasebe, K. Nishinari, Y. Sugiyama, S. Tadaki, S. Yukawa, New J. Phys. **11**(8), 083025 (2009)
9. S. Tadaki, M. Kikuchi, M. Fukui, A. Nakayama, K. Nishinari, A. Shibata, Y. Sugiyama, T. Yosida, S. Yukawa, New J. Phys. **15**(10), 103034 (2013)
10. Nagoya Dome Ltd., http://www.nagoya-dome.co.jp/
11. L. Neubert, L. Santen, A. Schadschneider, M. Schreckenberg, Phys. Rev. E **60**, 6480 (1999)

http://www.springer.com/978-3-319-10628-1

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