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Empirical Phase Diagram of Congested Traffic Flow

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We present an empirical phase diagram of the congested traffic flow measured on a highway section with one effective on-ramp. Through the analysis of local density-flow relations and global spatial structure of the congested region, four distinct congested traffic states are identified. These states appear at different levels of the upstream flux and the on-ramp flux, thereby generating a phase digram of the congested traffic flow. Observed traffic states are discussed in connection with recent theoretical analyses.

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Rich physical phenomena in traffic flow have been investigated by both empirical and theoretical studies. Two distinct traffic states, the free flow and the traffic jam state, have been identified from measurements on homogeneous highways [1] and various properties of them have been successfully reproduced by traffic models [2].

Further empirical studies [3,4] have reported the presence of additional traffic states, where typical vehicle velocities take intermediate values between the velocity levels of the free flow and the traffic jam. In these states, vehicle motions in all lanes are synchronized and the notion of a unique density-flow relation breaks down. From local traffic patterns, three different types are classified [3]. These congested traffic states [5] appear mostly near ramps and theoretical studies [6,7] of the ramp effects reproduced some of their features such as the discontinuous transition from the free flow to the congested flow and the high flux level of the congested flow.

Recently, more extensive theoretical studies [8,9] have revealed that for highways with an on-ramp, several distinct congested traffic states appear depending on the levels of the upstream flux and the on-ramp flux. A phase diagram is constructed [8,9] and metastabilities between these states are also investigated [9]. Yet the relation between these studies and the observations [3,4] is not clear and especially no empirical evidence for the predicted phase diagram has been reported to our knowledge.

In this Letter, we present an analysis of the congested traffic flow measured on a highway in Seoul, Korea. From the studies of the traffic patterns at fixed locations and the global spatial structures, we find 4 qualitatively distinct congested traffic states. Appearance of each state depends on the upstream flux and the on-ramp flux, from which we construct the empirical phase diagram. These 4 states exhibit features that agree with theoretical studies [8,9]. But differences are also discovered.

For the study, we use the traffic data of the Olympic Highway which connects the east and west ends of Seoul. Since it is an intra-city highway, there are many ramps and the spacings between them are rather short (~ 1 km). But in some sections, lane dividers separate the lane 1 and 2 from the lane 3 and 4, and as a result, the two inner lanes become a ramp-free highway. Our investigation is focused on a 14 km east-bound section, between Seoul bridge and Young-dong bridge, that contains a long (≈ 5 km) lane divider [10]. In this section, 6 on-ramps and 6 off-ramps exist (all of them connected to the outermost lane 4) and 15 image detectors record the flux q and the average velocity v for each lane at every one minute interval [Fig. 1(a)]. Among the ramps located outside the ideal ramp-free region, usually only one or two of them are effective and the flux through other ramps are small. For the analysis, inner-lane traffic data for 14 different days in June and July, 1998 are used. We search congested traffic states that are long-lived (~ 1 hour) and appear practically everyday. In this way, we identify 4 congested traffic states, for each of which, data for a particular day are presented below to demonstrate its typical features.

The first kind of the congested traffic states, which we call CT1, is shown in Fig. 1(b), where the on-ramp ON3 at $x = 8.6$ km is the main ramp in the time interval depicted in the figure and the traffic between $x \approx 3$ km and $x \approx 10$ km is congested. The spatial extension of the congested region does not expand with time (within our estimated accuracy of 1 km/h) but the boundaries of the region are not stationary. Also systematic oscillation develops spontaneously near the upstream boundary, which is manifest in the velocity vs. time plot at D4 [Fig. 1(c)]. Notice that the velocity oscillation is amplified and its period is enhanced as the upstream boundary is approached. Peaks of the velocity move with velocity ~ -13 km/h. Similar features are reported in Ref. [11]. We mention that the oscillation is not caused by the temporal variations in the upstream flux. Another charateristic of the CT1 state is the two-dimensional covering of the density-flow relation [Fig. 1(d)].

The second kind of the congested traffic states, CT2, is shown in Fig. 2(a), where the effective ramp is ON3. The density-flow relations cover two-dimensional areas [Fig. 2(b)]. In contrast to the CT1 state, however, the boundaries of the congested region are almost motionless and the development of the large amplitude oscillation is not observed [Fig. 2(c)] even though the velocity levels are comparable to those in the congested region of the CT1 state.

The third kind of the congested traffic states, CT3, is shown in Fig. 3(a), where the effective ramp is ON4. The boundaries of the congested region are again motionless. The congested region is much shorter compared to the CT1 and CT2 states. More important difference appears in Fig. 3(b). The density-flow relation at each detector location inside the congested region forms a straight line, implying that the velocity ($v = q/\rho$) remains almost constant even under the significant flux fluctuations. However the values of the velocity are different for different detectors. [In 3 out of 14 investigated days, we also observe a wide congested region ($\sim$ 4 km) with the stationary and almost *homogeneous* velocity profile. Here we do not present this as another distinct traffic state since the number of available data sets is too small.]

The fourth and the last kind of the congested traffic states, CT4, is shown in Fig. 4, which appears during morning rush hours. The effective ramp is ON3. While the downstream boundary of the congested region remains stationary, the upstream boundary propagates backwards and the congested region expands monotonically, unlike all other congested traffic states mentioned above. The expansion rate is higher for the higher level of the flux in the upstream region where the free flow is maintained, and the observed values of the rate range from 2.2 km/h to 8.8 km/h. The density-flow relation covers a two-dimensional area and the development of the large amplitude oscillation is not observed.

We examine differences in the appearance conditions of the 4 congested traffic states. Recent theoretical studies using one lane models [8,9] suggest that the flux level $f_{\rm up}$ at the right upstream of the congested region, where the free flow is maintained, and the on-ramp flux $f_{\rm rmp}$ are the two important control parameters. These studies assume an ideal situation where $f_{\rm up}$ and $f_{\rm rmp}$ are constants. While they fluctuate in reality, however, dominant fluctuations come from short time scale (one minute) variations and the fluctuations are greatly suppressed in long time scale (ten minutes or longer). Thus we use the average values of $f_{\rm up}$ and $f_{\rm rmp}$ over the time intervals (typically 1 hour long) during which a particular state is maintained [12]. In Fig. 5, each point ($f_{\rm rmp}$, $f_{\rm up}$) thus obtained is marked with a different symbol depending on the maintained congested traffic state. Notice that although there are some overlaps, each symbol occupies a clearly distinguishable region in the $f_{\rm rmp}$-$f_{\rm up}$ plane. This difference in the data locations verifies the roles of $f_{\rm rmp}$ and $f_{\rm up}$ as important control parameters, in agreement with Refs. [8,9]. Also the metastability between the free flow and the CT1, CT2, CT3 states is observed as studied in Ref. [9].

We now make a detailed comparison of the measurement data with the theoretical studies [8,9]. The CT1 state is similar to the recurring hump (RH) state in Refs. [6,9]. In both states, the congested regions do not expand and systematic oscillations develop. The oscillation in the CT1 state, however, exhibits features that are not shared by the RH state, such as the oscillation amplification and the period enhancement [13]. The CT2 state can be related to the pinned localized cluster (PLC) state [8,9] [in Ref. [9], a different term "standing localized cluster" (SLC) state is used to denote the same state]. In both states, the congested region does not expand and no systematic oscillation develops. Also the spatial variation of the long time ($\sim$ 1 hour) averaged density-flow relations from the upstream to the downstream is essentially identical to the pattern for the PLC state [Fig. 2(b) in Ref. [9]]. And the data locations of the CT2 state in the $f_{\rm rmp}$-$f_{\rm up}$ plane [Fig. 5] are to the left of those of the CT1 state, which agrees with the relationship between the PLC and the RH state [9]. The two-dimensional covering of the density-flow plane in the CT1 and CT2 states, on the other hand, is not shared by the RH and PLC states. We speculate that the covering property may be due to fluctuations effects that are not taken into account in Refs. [8,9]. For example, it is recently demonstrated that fluctuations in vehicle types can generate the two-dimensional covering [14]. We also suspect that short time scale fluctuations in $f_{\rm up}$ and $f_{\rm rmp}$ may generate a similar effect.

The CT3 state is also similar to the predicted PLC state in regard to the stationary boundaries of the congested region and the absence of the systematic oscillations. The data locations of the state in the $f_{\rm up}$-$f_{\rm rmp}$ plane [Fig. 5] are also in reasonable agreement with those of the PLC state [8,9]. However the property of the constant velocity in this state is not shared by the PLC state. This property implies that the car following dynamics in this state is significantly different from that assumed in many theoretical models [2,7], that is, the velocity adjustment to the spatial gap.

The CT4 state can be related to the oscillating congested traffic (OCT) state or homogeneous congested traffic (HCT) state [8,9], both of which exhibit the expansion of the congested region to the upstream. In theoretical studies, it is found that the congested region of the OCT state contains large clusters with the jam character while the congested region of the HCT state is homogeneous [8,9]. The density-flow relation of the CT4 state does not demonstrate the characteristic line of the jam, which suggests that the HCT state is the proper theoretical counterpart of the CT4 state. As for the two-dimensional covering property of the CT4 state, we mention that the same covering can be reproduced for the HCT state [14]. Also the data locations of the CT4 state in the phase diagram are consistent with the prediction for the HCT state.

We next compare our data with the German highway data in Ref. [3], where congested traffic flows are classified into 3 types (i,ii,iii) according to local density-flow relations without much regard to spatial structures. In this classification, the CT1, CT2, and CT4 states with non-stationary density-flow relations belong to the type (iii), and the CT3 state with the stationary velocity property to the type (ii). We also observe the type (i) state that is characterized by the stationary velocity and density pro-

files. However, this state is always short-lived (less than 5 minutes), which is too short for our analysis, and we do not include this state in our classification.

It is also interesting to compare the CT1 state with the congested traffic state reported in Ref. [11], which we call CT1' state tentatively. In both states, the amplification and the periodicity enhancement of the velocity oscillation occur and the average velocity levels rise during the amplification. On the other hand, the velocity oscillation in the CT1' state grows to generate mature jam clusters and the density-flow relation approaches the characteristic line (the line J in Ref. [11]) of the traffic jam, while this feature is absent in the CT1 state [see Fig. 1(d)]. This difference suggests that the CT1 and CT1' states may be distinct congested traffic states. They also seem to appear at different regions in the $f_{\rm rmp}$-$f_{\rm up}$ plane. From the data give in Ref. [11], we estimate $f_{\rm up} \geq 1600$ veh/h (information for $f_{\rm rmp}$ is not available) for the CT1' state (compare with Fig. 5). A recent study [15] also suggests that the CT1' state is related rather to the theoretically predicted OCT state [8,9], instead of the RH state.

In summary, 4 congested traffic states are identified by combining temporal traffic patterns at fixed locations and spatial structure of the congested region. It is found that these 4 states appear at different levels of the upstream flux and the on-ramp flux. An empirical phase diagram is constructed and compared with recent predictions. Many properties of the observed states agree with predictions but deviations are also found. Lastly we mention that there exist regions in the $f_{\rm rmp}$-$f_{\rm up}$ plane which are not probed by our data. Thus it is possible that additional congested traffic states exist in those regions. Further investigation is necessary.

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[10] To be precise, the lane divider is not perfect at two locations where a small number of vehicles can be exchanged between the lanes 2 and 3.

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[12] Both quantities are averaged over the two inner lanes. And $f_{\rm rmp}$ is estimated from the difference between the maximum flux level near the downstream end of the congested region and the flux level near the upstream end of congested region.

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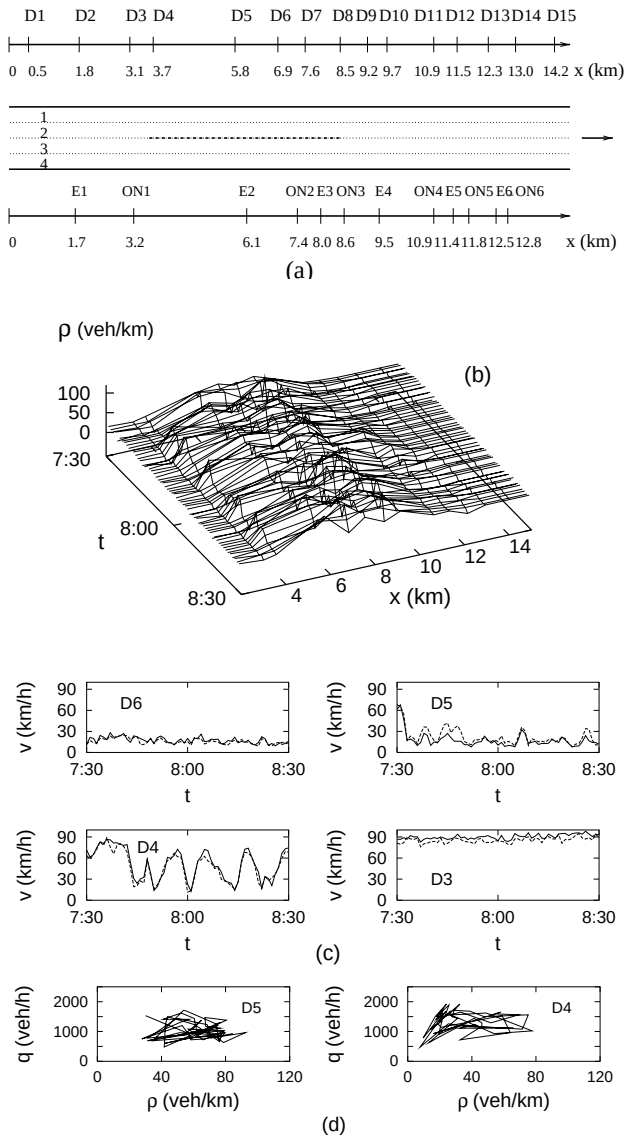

FIG. 1. (a) Detector (Dn), on-ramp (ONn), and off-ramp (En) locations in the Olympic Highway section studied in this work. The dashed line in the middle denotes the lane divider. (b) The 3D density profile of the CT1 state. (c) Velocity vs. time plots at different detectors (solid line for the lane 1 and dashed line for the lane 2). The stop-and-go pattern appears at D4 but the free flow is observed at D3. (d) The density-flow relations at D5 and D4 from 7:30 to 8:30 data. The characteristic line of the traffic jam does not appear.

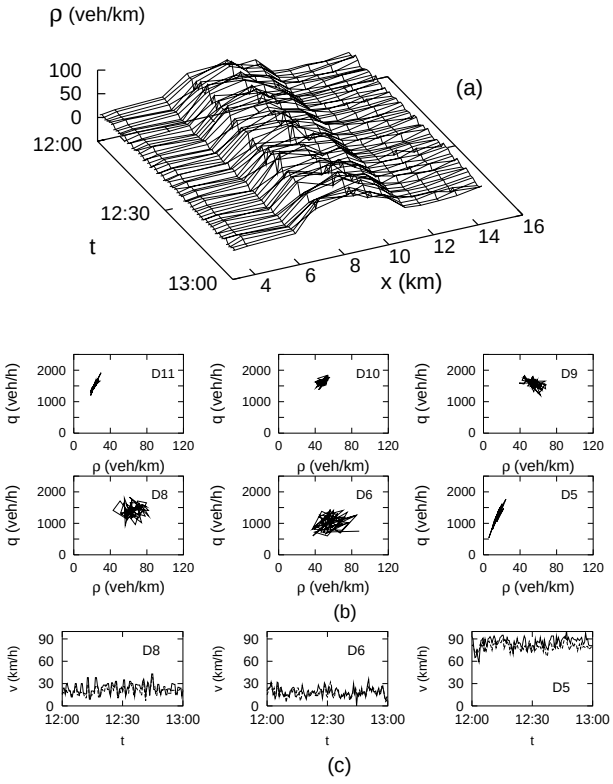

FIG. 2. The 3D density profile (a), density-flow relations (b), and velocity vs. time plots (c) of the CT2 state. In contrast to the CT1 state, the amplification of the velocity fluctuations does not occur.

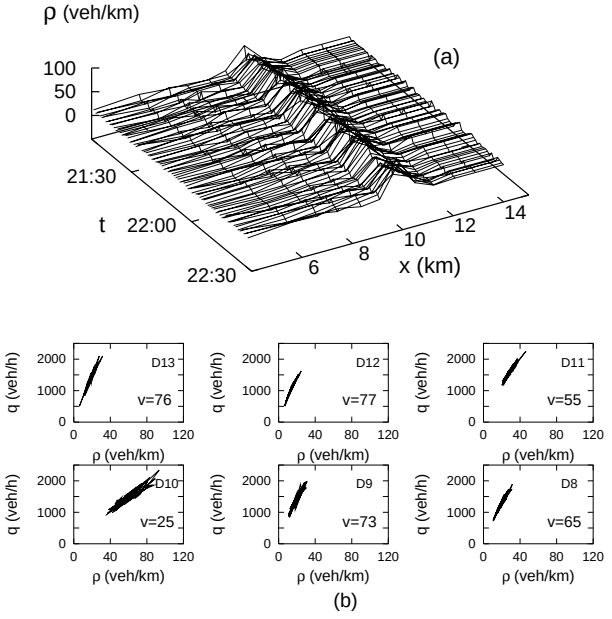

FIG. 3. The 3D density profile (a) and density-flow relations (b) of the CT3 state. The velocity remains almost constant at each detector.

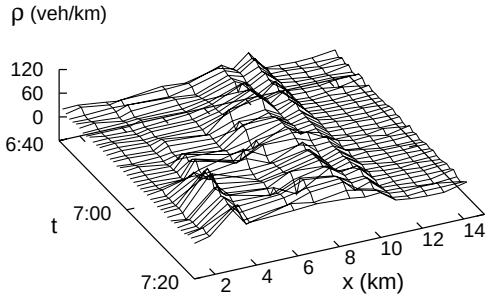

FIG. 4. The 3D density profile of the CT4 state.

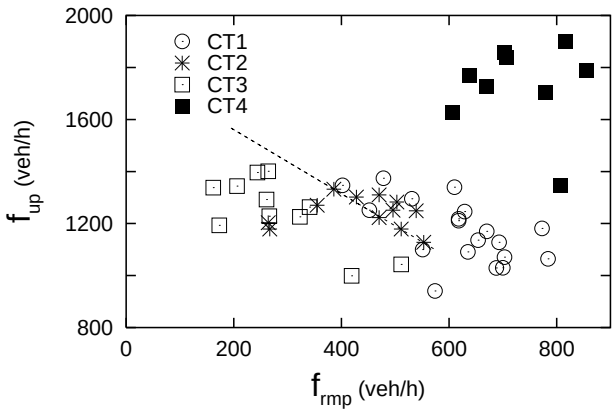

FIG. 5. The phase diagram of the four congested traffic states on the Olympic Highway. The upstream flux $f_{\rm up}$ and the on-ramp flux $f_{\rm rmp}$ are average values over the time interval during which a particular congested traffic state is maintained. The free flow is also observed below the dashed line.