Field measurement analysis to validate lane-changing behavior in a cellular automaton model

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In the present study, we analyzed field measurement data obtained for a Japanese expressway and used it as a data set for the validation of microscopic simulation models. Consequently, in accordance with previous studies, we confirmed the common features depicted by the fundamental diagram (flux vs density relation) and lane-usage ratio vs density diagram. We found two things regarding lane-changing behavior: (1) a lane change occurs asymmetrically, where a lane change from a slow to a fast lane differs from that from a fast to a slow lane; and (2) the so-called incentive criterion in the case of small gaps between the preceding vehicles in both slow and fast lanes refers to the velocities and /or the relative velocities with respect to the preceding vehicles, whereas that for relatively large gaps refers to the distances to the preceding vehicles is cast into the above incentive criterion in addition to the two factors mentioned above.

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I. INTRODUCTION

For the past several years, a growing social concern has pushed many statistical physicists to address the problem of modeling the traffic flow. Mathematically speaking, we can treat traffic flow as a “fluid” from a macroscopic viewpoint (Eulerian scope) and also as “a set of self-driving particles” from a microscopic viewpoint (Lagrangian scope). The microscopic concept is subsequently divided into two models: the car-following model where both time and space are continuous and the cellular automaton (CA) model where time and space are completely discrete (e.g., [1–4]). CA models have been extensively applied because of their flexibility to reproduce a realistic traffic flow ever since the first CA traffic model, i.e., the Nagel-Schreckenberg model [5], was proposed in 1992. Moreover, unlike a macroscopic model, which is formulated by a set of partial equations of fluid dynamics, i.e., a set of kinetic equations, CA can easily take into account the lane-changing behavior, each of a vehicle in both branching and merging of several roads, such as an entry (exit) to (from) an expressway, influence of a toll gate, etc. In view of the applications of the CA model to scientifically and practically interesting problems, a submodel for a driver’s lane-changing behavior is the most important one to be considered. In fact, we have been investigating whether a social dilemma structure that can be described by a clear mathematical expression by the evolutionary game theory in the so-called bottleneck situation case for lane-closing and frequent lane-changing scenarios with a realistic traffic flow can be observed [6–9]. Modeling of realistic lane changes using CA has been quite demanding in terms of deriving meaningful and reliable numerical results.

Incidentally, submodels accounting for a vehicle’s lane change on the basis of the CA framework and several alternatives have been presented. All these alternatives basically comprise two conditions: incentive and security criteria. The incentive criterion refers to the driver’s motivation for changing lanes, while the security criterion refers to a threshold condition of whether a lane change is safe. Both criteria are expressed by inequalities defined by several specified distances between a focal vehicle and its preceding vehicles in both the current and destination lanes or the following vehicle in the destination lane (e.g., [10–21]). Regarding the incentive criterion, most of the previous studies only refer to the distances between vehicles in both the current and destination lanes. Kerner and Klenov [22], however, developed a lane-changing CA model based on the velocity difference between neighboring vehicles. Moreover, we developed a model that defines the incentive criterion considering both the distance and velocity difference between the preceding vehicles in the current and destination lanes [23]. All the aforementioned submodels define each of the incentive criteria empirically. Although they have been expected to be plausibly working, they have not been proven based on behaviors of real drivers. In particular, the answer to the question whether a driver is motivated to make a lane change because of insufficient distance in the current lane but a sufficient one in the destination lane (only distances motivated) or because of a negative velocity difference in the current lane but a positive one in the destination lane (meaning the driver can accelerate in the neighboring lane; velocity-difference motivated) is not clear because of the lack of field measurement data.

Therefore, in this work, we report a complete data set that addresses all of the above-mentioned issues; this data set was acquired for a Japanese expressway.

This report is organized as follows: Section II describes our field measurement setup and the procedure of data handling, Sec. III presents and discusses the results, and Sec. IV gives a summary.

II. MEASUREMENT SETUP AND DATA HANDLING

Our field measurements were conducted between May 3rd and May 6th, 2014, by overlooking a section of the Kyushu Expressway using several cameras connected independently to notebook-type PCs for data acquisition. As shown in Fig. 1(a), the observation site was positioned at the clifftop of Mt. Otogana overlooking the expressway, where the cameras could appropriately view all four lanes of traffic. However,

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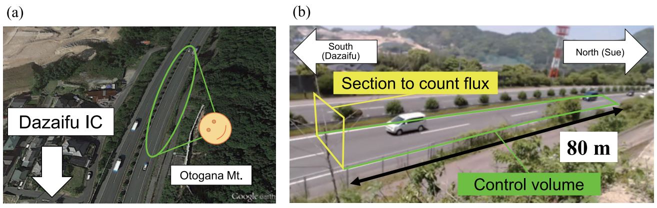

FIG. 1. The left panel illustrates the measurement site on Kyushu Expressway where cameras were installed on the clifftop of Mt. Otogana, 2.1 km north of the Dazaifu Interchange (Otogana, Onojo City, Fukuoka Prefecture). The image is taken from Google Earth. The right panel shows the definitions of the control volume (CV) and the cross section used to count the number of passing vehicles for the measurements of traffic flux, average velocity, density, lane-usage ratio, and frequency of lane change. The length of the CV is 80 m.

we focused on the two lanes with traffic flow in the southern direction. As shown in Fig. 2(b), an 80-m-long control volume was placed on the expressway and a cross section of the expressway was selected to count the number of passing vehicles.

We follow our previous work [24] in order to handle the acquired data to obtain a traffic flux, density, and lane-usage ratio.

Unlike the loop detector data, motion picture data allow the analysis of each vehicle via the Lagrangian approach.

We first define the 12 vehicle classes illustrated in Fig. 2 and their respective equivalent lengths (ELs) normalized to the actual length of a standard sedan-type vehicle, i.e., $L_{\text{sedan}} = 4.92$ m.

Next, we separately count the number of vehicles belonging to each of the respective classes passing through the cross section set at the downward of the control volume per unit time [see Fig. 1(b)]. Specifically, we capture $\Sigma N_i{}'$ [(vehicles)/(15 s)], where i indicates one of the 12 classes. In the present study, we rely on the total equivalent number of vehicles $\Sigma N_i{}' \times \text{EL}_i (= \Sigma N_i)$ [(vehicles)/(15 s)] instead of $\Sigma N_i{}'$, where in a nutshell, $\Sigma N_i{}'$ is converted into the total number of standard sedan-type cars based on their lengths. ΣN_i can be transformed into the total flux $q = \Sigma q_i$ [(vehicles)/s]. Simultaneously, we focus on each of the vehicles passing through the cross section during the measurement period. By manipulating the motion picture back and forth, we derive the running time of a particular vehicle between the upper and lower boundaries of the control volume and transform this information into the velocity of the vehicle. At the end of this data analysis, we can obtain the average velocity by dividing the control volume by the average running time of vehicles over a 15-s period, i.e., $v = 80/(\Sigma$ the running time of a particular vehicle over a 15-s period / $\Sigma N_i{}')$ [m/s]. Consequently, we can estimate the density ρ[m/m](= [ND]) over a 15-s period to measure both flux and velocity by calculating $\rho[\text{m/m}] = L_{\text{sedan}}(q/v)$. The density ρ is separately evaluated for each of the two lanes.

For calculating the lane-usage ratio, we determine it by taking the arithmetic mean of four successive time sections of density over $4 \times 15 - [\text{s}](= 60 - [\text{s}])$.

III. RESULTS AND DISCUSSION

A. Basic characteristics of the flow field

We first confirm that the acquired data show the typical characteristics of conditions that have been observed on Japanese expressways.

Figure 3 shows the fundamental diagram for both lanes. We can clearly observe the presence of two divided regions of the plot consisting of orderly and more scattered arrangements of the data points for the respective lanes. The former region consists of the free phase followed by the metastable phase, while the latter indicates the high-density phase. Although the data points in the figure seem to be too scattered to distinguish, the high-density phase may contain a synchronized phase, which is supported by Kerner's three-phase theory [4], and a jam phase. From the former sets of plots, we can derive an average velocity for the free phase from the respective slope of the regression line. It clearly indicates that the average velocity in the slow lane is lower than that in the fast lane. The corresponding two slopes are approximately comparable to the maximum velocity of 100 km/h on a Japanese expressway.

As shown in Fig. 3, the peak flux of the fast lane is obviously larger than that of the slow lane. This implies that the fast lane allows vehicles to travel at a higher speed in a compact manner

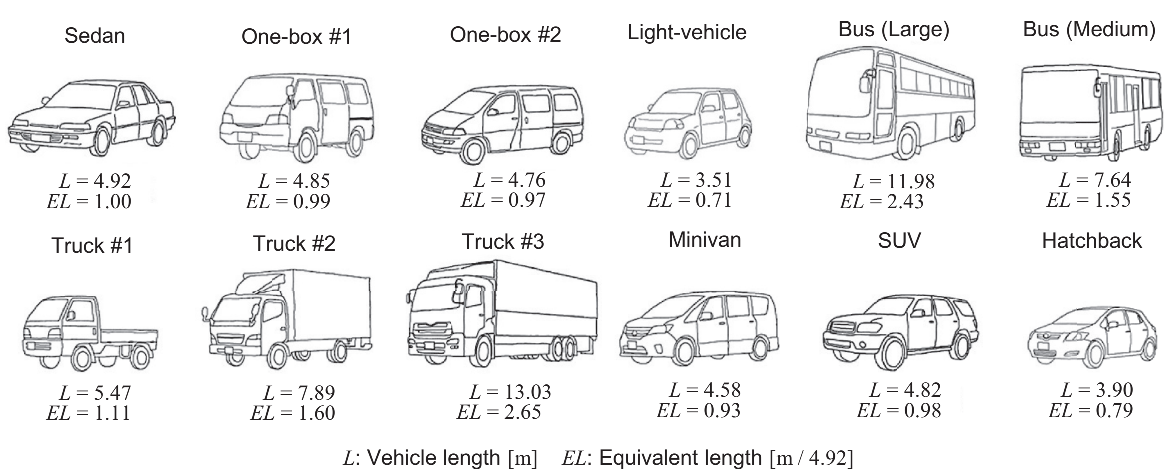

FIG. 2. Actual vehicle lengths and equivalent lengths (ELs) for each of the 12 vehicle classes.

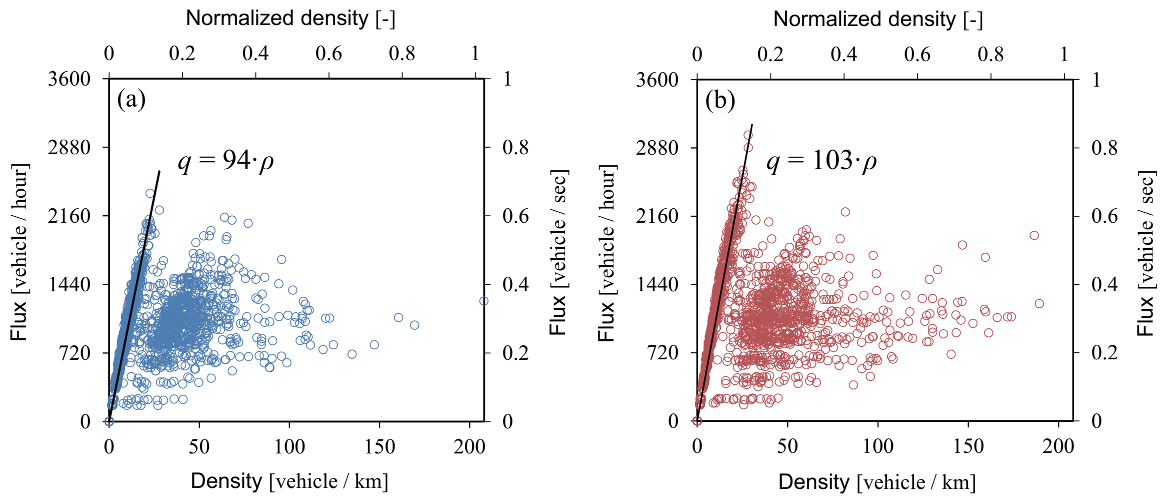

FIG. 3. Fundamental diagrams showing the traffic flux density; (a) for the slow lane and (b) for the fast lane. Here, it should be noted that there is an anomalous data plot whose normalized density is greater than 1 (approximately 1.02) in a jam phase in Fig. 3(a). This erratic data is just due to the minute measurement errors of both the velocity and the flux.

compared with the speed the condition in the slow lane allows; this is known as a "platoon formation."

The fundamental diagram that we obtained in the present study shows analogous features to the previous studies of conditions on other Japanese expressways [24,25].

Figure 4 shows the relationship between the lane-usage ratio and mean density of the two lanes expressed in physical dimensions [(vehicles)/km/lane] and the mean normal density as a secondary horizontal axis. A lager ratio indicates that a majority of vehicles travels in the slow lane. What we can note as a general tendency is that a majority of vehicles stays in the slow lane as long as the mean density remains sufficiently low, and even with increasing density, there seems to be no obvious difference in the observed trend despite a larger scattering between the slow and fast lanes. This observation is justified because there is no incentive to change lanes from the slow lane to the fast lane as long as every vehicle travels at maximum velocity. The flow field at a relatively high density does not allow frequent lane changes; this reduces the advantage of staying in the fast lane. One notable point is that there is a density range between the low and high densities where the majority is in the fast lane rather than in the slow lane. This "inversion" tendency was also reported in our previous study [24]. As mentioned, its existence can be justified as follows. At moderate traffic density, a driver that faces a preceding vehicle traveling at a low speed in the slow lane would try to overtake the slow vehicle by making a lane change in order to keep traveling at the free-phase velocity. If this happens frequently, a low lane-usage ratio would be realized. This may usually happen in an expressway that has a lane-changing policy such as that of Japanese expressways, where regular driving lanes and lanes for overtaking are rigorously defined.

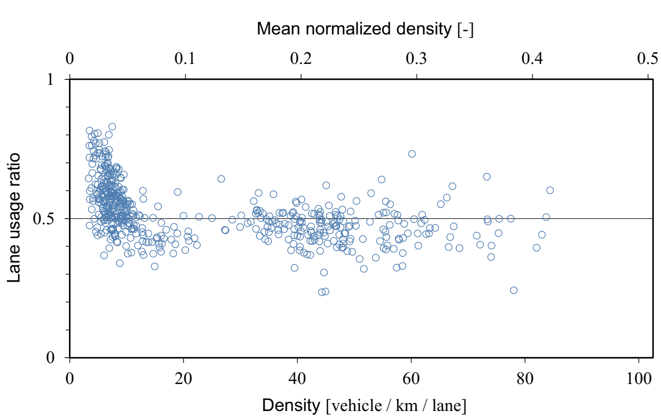

FIG. 4. Lane-usage ratio vs mean density of the two lanes with mean normal density as a secondary horizontal axis.

As seen in Figs. 3 and 4, the data set we obtained shows typical features commonly observed on Japanese expressways.

B. Lane-changing behavior

Herein, the incentive criterion in a typical conventional lane-changing submodel of the CA model is described [7,23]:

$$\mathrm{gap}_p^f \leqslant v_i^{(p)} \quad \text{and} \quad \mathrm{gap}_n^f \geqslant v_i^{(p)}, \tag{1}$$

where gap_p^f is the number of unoccupied sites in front of the focal vehicle (agent i) in the same lane and gap_n^f is the number of unoccupied sites in front of the focal vehicle in the destination lane (see Fig. 1). The incentive criterion indicates that it is rational to attempt a lane change to attain higher speed than to stay in the same lane. Instead of following this conventional idea, we propose a new incentive criterion that considers the relative velocities defined by subtracting the velocities of the preceding vehicles in both lanes from that of the vehicle under consideration as follows [23]:

$$\mathrm{gap}_p^f \leqslant v_i^{(p)} - v_{i+1}^{(p)} \quad \text{and} \quad \mathrm{gap}_n^f > v_i^{(p)} - v_{i+1}^{(n)}, \tag{2}$$

where $v_{i+1}^{(p)}$ is the velocity of the preceding vehicle (agent $i+1$) in the same lane and $v_{i+1}^{(n)}$ is the velocity of the preceding vehicle in the opposite lane (Fig. 5). The crucially important difference between Eq. (1) and Eq. (2) is whether

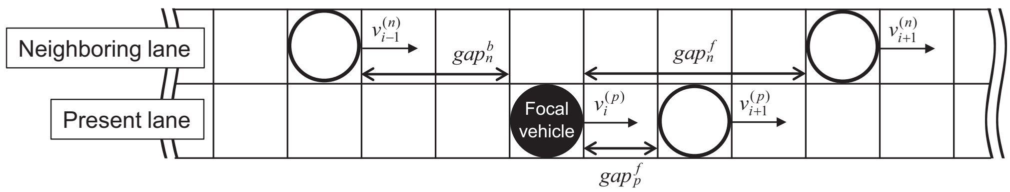

FIG. 5. The assumed situation of a car agent changing lanes that shows the definitions for gaps and velocities. The black circle indicates the focal vehicle and the white circles indicate neighboring vehicles.

a driver evaluates his own velocity or the relative velocity defined by the difference between his own velocity and that of the preceding vehicle. Reference [23] showed the results of numerical simulations and concluded that the latter submodel, i.e., Eq. (2), results in more frequent lane changes, especially in the high-density region, than Eq. (1) does because a low velocity hardly agrees with Eq. (1) but possibly satisfies Eq. (2). Our experience certainly reminds us that there might be several aggressive drivers who seek overtaking accompanied with forceful lane changing even in a traffic congestion situation. Qualitatively speaking, we can apply either Eq. (1) or Eq. (2) depending on various situations of traffic flows, but there is a lack of proven knowledge regarding this point. In this study, we analyze the measurement survey of real traffic flow in order to provide an incentive criterion for lane-changing events from the perspective of gap (that is, distance) and (relative) velocity with respect to the preceding vehicles motivated by their works [7,23].

Figure 6 shows the relation of the gaps between the focal vehicle and a preceding vehicle in the present and neighboring lanes, i.e., gap_p^f and gap_n^f, respectively. Panel (a) shows the case for a lane change from the slow lane to the fast lane and panel (b) shows that from the fast lane to the slow lane. Panel (c) shows the schematic which describes how to calculate each vehicle's velocity and to obtain gap_p^f and gap_n^f.

The data consist of all actually observed lane changes. Thus, we cannot use any arguments regarding the lane-change frequency or probability, i.e., how frequent a lane change takes place under certain gap conditions. But, again, the data shown here indicates the conditions for which a lane change actually takes place.

The shown data does not contain any information about the vehicle's velocity. It is unnecessary to discuss whether all data correspond to the incentive criterion because it would definitely mean that Eq. (1) is valid irrespective of the value of $v_i^{(p)}$ as long as a data point is observed above the 45° line.

One crucially important observation in Fig. 6 is that the majority of actual lane-change events are plotted above the 45° line in the case of a vehicle changing lanes from the slow lane to the fast lane. More precisely, this tendency seems clear for the data outside the green-highlighted region, which implies that a vehicle can maintain sufficiently large distances with preceding vehicles in both lanes. However, as long as a vehicle maintains insufficient distances, the incentive criterion expressed by Eq. (1) does not seem valid. This point will be addressed below in the discussion of Fig. 7.

Figure 6(b) clearly shows that the incentive criterion of Eq. (1) does not come into effect. Obviously, actual lane-change events take place rather randomly and irrespective of gap_p^f and gap_n^f. That seems natural because the Japanese traffic regulation determines the difference between a slow and fast lane and a vehicle must principally travel in the slow lane and is allowed to use the fast lane only for overtaking a preceding slow vehicle in the same slow lane. Thus, a vehicle is expected to return to the usual running lane, i.e., the slow lane, immediately after completing an overtaking event. Therefore, the incentive criterion cannot be applied to a case when a vehicle changes from a fast lane to slow lane as long as the Japanese expressway policy is concerned.

Figure 6(a) implies that Eq. (1) does not apply if a vehicle has less than sufficient distances with the preceding vehicles in the present and neighboring lanes. Figure 7 shows an enlarged image of the green-highlighted region of Fig. 6(a), where both distances are less than the length of the control volume (80 m) but classifies the plots into three classes. A red plot means a vehicle for which $v_{i+1}^{(p)} - v_i^{(p)} < 0$ and $v_{i+1}^{(n)} - v_i^{(p)} > 0$; this implies that the vehicle unfailingly accelerates during a lane change. A light-gray plot indicates a vehicle for which $v_{i+1}^{(p)} - v_i^{(p)} < 0$ and $v_{i+1}^{(n)} - v_i^{(p)} < 0$; this implies that there is no possibility of acceleration during a lane change. A dark-gray plot means $v_{i+1}^{(p)} - v_i^{(p)} > 0$ and $v_{i+1}^{(n)} - v_i^{(p)} > 0$; this implies that the vehicle does change lanes but can accelerate while staying in the present lane. None of the data is classified by the conditions $v_{i+1}^{(p)} - v_i^{(p)} > 0$ and $v_{i+1}^{(n)} - v_i^{(p)} < 0$. At a glance, we can note that a vast majority of the acquired data falls into the class with $v_{i+1}^{(p)} - v_i^{(p)} < 0$ and $v_{i+1}^{(n)} - v_i^{(p)} > 0$. Figure 8 shows three types of fraction as a function of the gap range with front vehicle in lane for the case of changing from the slow lane to the fast lane. A diamond-shaped data point indicates the proportion of the number of vehicles with $v_{i+1}^{(p)} < v_{i+1}^{(n)}$ to the total number of vehicles in each gap range; it is the fraction of the vehicles which change the lane motivated by the velocities of the preceding vehicles. A cross data point indicates the proportion of the total number of vehicles with $v_{i+1}^{(p)} - v_i^{(p)} < 0$ and $v_{i+1}^{(n)} - v_i^{(p)} > 0$ (the total number of the red data points as shown in Fig. 7) to the total number of vehicles in each gap range with front vehicle in lane; it is the fraction of the vehicles which change from the slow lane to the fast lane motivated by the relative velocities with respect to the preceding vehicles. A bar chart indicates the proportion of the total number of vehicles in the region above the 45° line in Fig. 6 (the total number of the data points with $\text{gap}_p^f < \text{gap}_n^f$) to the total number of vehicles in each gap range with front vehicle in lane; it is the fraction of the vehicles which change from the slow lane to the fast lane motivated by both gaps with respect

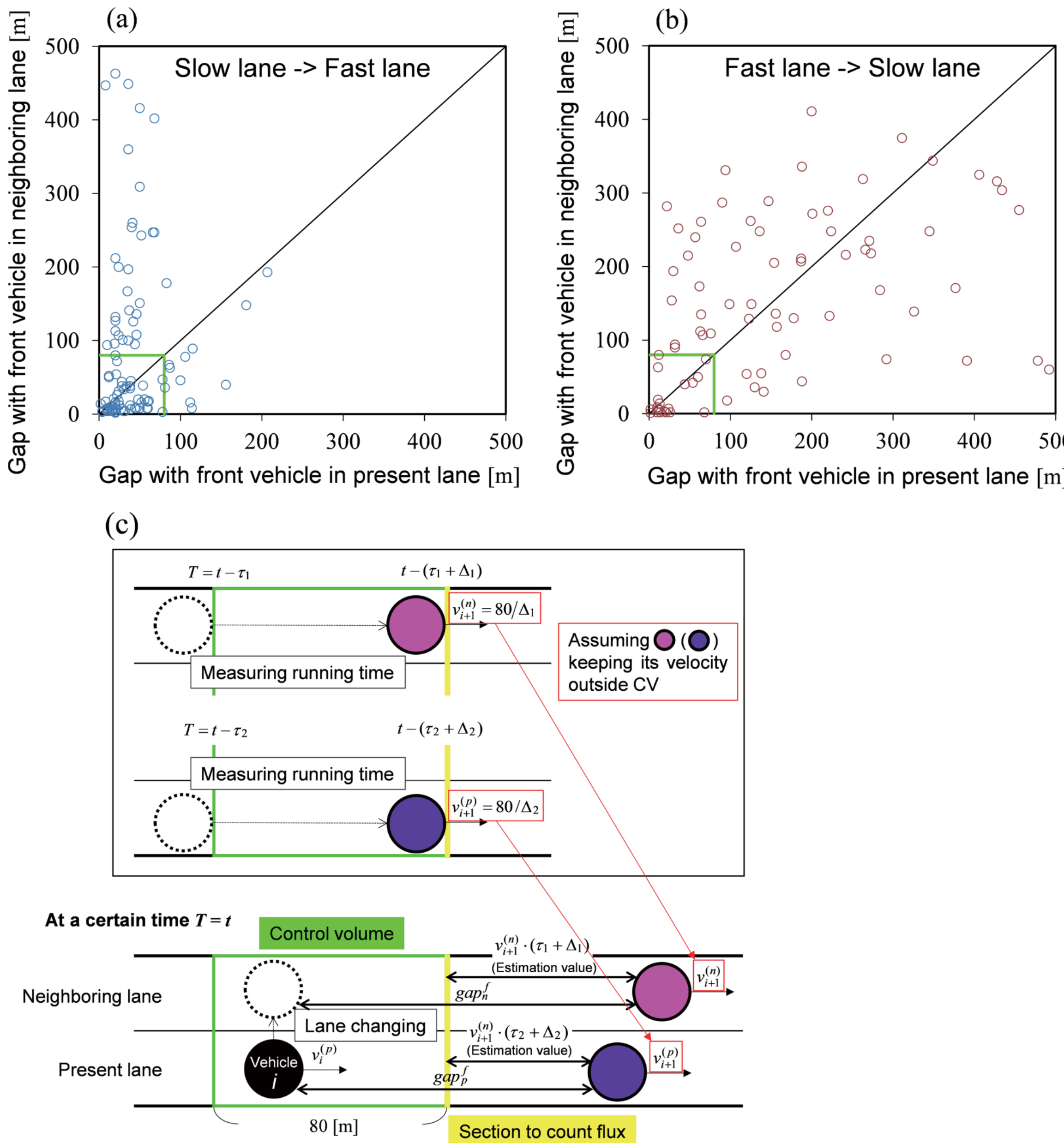

FIG. 6. The gaps between the focal vehicle and neighboring vehicles in the present and neighboring lanes for lane change from (a) slow lane to fast lane and (b) fast lane to slow lane. The green-highlighted regions indicate the control volume. Note that the gaps are estimated by assuming the foregoing vehicles in each lane keep their own velocities even if they go outside the control volume, which were measured when they passed inside the control volume as shown in (c).

to the preceding vehicles. As can be seen from Fig. 8, it turns out that not only the relative velocities but also the velocities of preceding vehicles themselves are building blocks of the incentive criteria for the entire gap ranges (distances against the preceding vehicles). Meanwhile, when the gap exceeds 60–99 [m] highlighted in green, the fraction with regard to the distances illustrated by bars becomes greater than 0.5, so that the distance with respect to the preceding vehicles is also included in the incentive criterion in addition to the two factors mentioned above. Although the behavior of both the cross and the diamond-shaped data points in Fig. 8 provides important information to establish the incentive criterion, it does not enable us to identify the critical gap [m] where the incentive criterion changes (i.e., the boundary where the phase of the incentive criterion transits). Alternatively, we clearly find that the bars in Fig. 8 become saturated as the gap range exceeds 60–99 [m], which leads us to conclude that the gap range 60–99 [m] is the critical gap.

Summing up, we found three factors composing the incentive criterion: (i) the velocities of the preceding vehicles, (ii) the relative velocities with respect to the preceding vehicles, and (iii) the distances (gaps) with respect to the preceding vehicles. In addition, we identify the phase of the incentive criterion; for the region of short gap range (smaller than the critical gap, 60–99 [m]), the combination of (i) and/or (ii) constitute one of the phases, whereas for the region of long gap range greater

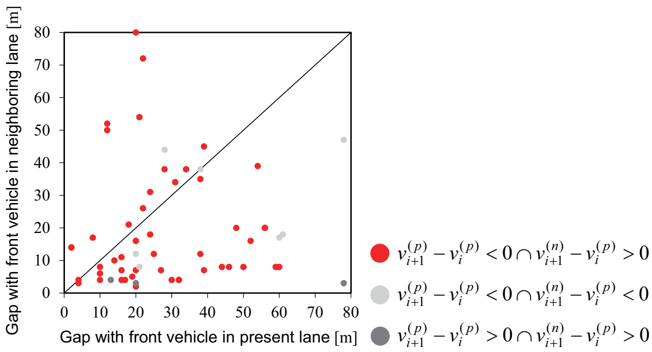

FIG. 7. The gaps between the focal vehicle and neighboring vehicles in the present and neighboring lanes for the case of a change from the slow lane to the fast lane. The figure shows the enlarged green-highlighted region of Fig. 6(a). A red data point indicates a vehicle with $v_{i+1}^{(p)} - v_i^{(p)} < 0$ and $v_{i+1}^{(n)} - v_i^{(p)} > 0$; this implies that the vehicle unfailingly accelerates by a lane change. A light-gray data point indicates a vehicle with $v_{i+1}^{(p)} - v_i^{(p)} < 0$ and $v_{i+1}^{(n)} - v_i^{(p)} < 0$; this implies the vehicle changes the lane but has no possibility of acceleration. A dark-gray data point indicates a vehicle with $v_{i+1}^{(p)} - v_i^{(p)} > 0$ and $v_{i+1}^{(n)} - v_i^{(p)} > 0$; this implies that the vehicle changes lane but can accelerate in the present lane as well. None of the data is classified by $v_{i+1}^{(p)} - v_i^{(p)} > 0$ and $v_{i+1}^{(n)} - v_i^{(p)} < 0$.

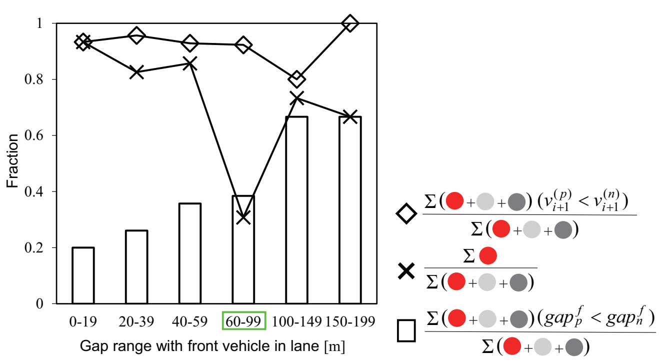

FIG. 8. Three types of fraction as a function of the gap range with front vehicle in lane for the case of a change from the slow lane to the fast lane. Red, light-gray, and dark-gray circles in the legends represent the same meaning in Fig. 7. A diamond-shaped data point indicates the proportion of the number of vehicles with $v_{i+1}^{(p)} < v_{i+1}^{(n)}$ to the total number of vehicles in each gap range; it is the fraction of the vehicles which change the lane motivated by the velocities of the preceding vehicles. A cross data point indicates the proportion of the total number of vehicles with $v_{i+1}^{(p)} - v_i^{(p)} < 0$ and $v_{i+1}^{(n)} - v_i^{(p)} > 0$ (the total number of red data points) to the total number of vehicles in each gap range with front vehicle in lane; it is the fraction of the vehicles which change the lane motivated by the relative velocities with respect to the preceding vehicles. A bar indicates the proportion of the total number of vehicles in the region above the 45° line in Fig. 6 (the total number of data points with $\text{gap}_p^f < \text{gap}_n^f$) to the total number of vehicles in each gap range with front vehicle in lane; it is the fraction of the vehicles which change the lane motivated by both gaps with respect to the preceding vehicles. The green-highlighted range corresponds to the critical gap, at which the incentive criterion changes from referring to the velocities and/or the relative velocities with respect to the preceding vehicles, to taking into account the distances with respect to the preceding vehicles in addition to the above two factors.

than the critical gap the factor (iii) is added to (i) and (ii) and all of these constitute another phase. Here, the constituents of the incentive criterion are expressed as follows:

$$\text{(i)} \quad v_{i+1}^{(p)} < v_{i+1}^{(n)}, \tag{3}$$

$$\text{(ii)} \quad 0 < v_i^{(p)} - v_{i+1}^{(p)} \quad \text{and} \quad 0 > v_i^{(p)} - v_{i+1}^{(n)}, \tag{4}$$

$$\text{(iii)} \quad \text{gap}_p^f < \text{gap}_n^f. \tag{5}$$

In this connection, Eq. (4) is identical to the condition for the red data point in Fig. 7, and identical also to Eq. (2) with replacing its left-hand sides by 0.

IV. CONCLUSIVE SUMMARY

To explore which incentive criterion triggers a lane-change event, we collected actual traffic flow data observed for a Japanese expressway. For the obtained data, the fundamental diagrams and lane-usage ratios were confirmed to show typical features reported for Japanese expressways.

A change from a fast lane to a slow lane happens irrespective of the incentive criterion because the Japanese traffic regulations demand that a vehicle must always travel in the slow lane except for the transient time when trying to overtake.

However, there are incentive criteria for changing from the slow lane to the fast lane underlying the actual events, but those are twofold. That is, we can identify the phase of the incentive criterion; for the region of short gap range (smaller than the critical gap, 60–99 [m]), the combination of (i) the velocities of the preceding vehicles and/or (ii) the relative velocities with respect to the preceding vehicles constitute one of the phases, whereas for the region of long gap range greater than the critical gap the factor (iii) the distances with respect to the preceding vehicles is added to (i) and (ii) and all of these constitute another phase.

In addition, we found that the results of this study justify the incentive criterion previously assumed for many CA models, e.g., the ones by Nakata *et al.* [7] and Kukida *et al.* [23]. Those come into effect in actual events but should be switched depending on the distances to the preceding vehicles. In this study, however, we do not directly verify the validity of Eq. (1) as well as Eq. (2) during the analysis of our measurement survey, but still at least we can conclude that it turns out that Eq. (4) comes to the same expression as the special case in Eq. (2) with replacing gap_p^f and gap_n^f by 0. This is because, as is the case for most CA models including their works, both the vehicle velocity and *gap* at one time step are treated as having the same dimension. Obviously, these variables have different dimensions in a real traffic flow system. As one of our future works, it is very important to verify directly the incentive criterion with regard to Eq. (1) and Eq. (2) in Refs. [7,23] from measurement survey (real traffic flow) in order to contribute to establishing a more realistic CA model concerned with the behavior of lane changing. To this end, we should investigate the correspondence of existing CA models and real traffic flow as a first step (for example, corresponding one time step in CA models with a real time [s] in real traffic flow, corresponding one cell (site) in CA models with a real distance

[m] in real traffic flow, corresponding the $V_{\max}$, which means the maximum velocity in CA models, with a real velocity [m/s] in real traffic flow, and so on). Finally, we make brief comments regarding the dramatic decrease of the cross data point at 60–99 [m] in Fig. 8. As for this matter, we still do not find any rationale to clarify the reason for this anomaly. Hence we should perform a thorough investigation into the causes of such a strange behavior as one of our future works; for example, we do additional research of observation surveys and deeper analysis with regard to lane-changing behavior in two lanes on expressways in a sort of similar situation.

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