高速道路における専用車線からの協調型自動運転車合流機会の評価のためのギャップ分布モデリング

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高速道路に協調型自動運転車（CAV）専用車線を設ける場合，専用車線の出口では，CAV が一般車線上の手動運転車に合流する必要性が生じる．本研究では，このような合流を想定した専用車線出口の設置位置の検討を行うことを目的として，手動運転車が形成するギャップ分布の分析を行った．阪神高速道路および中央自動車道により取得されたデータを対象に，異なる位置および交通条件下でのギャップ分布を合成ガンマ分布によりモデル化し，この分布に基づいて，CAV が手動運転車に合流するのにかかる余剰時間を算出した．その結果，上り坂が続くほど余剰時間は長くなる傾向があり，そのような地点への CAV 専用車線出口の設置は望ましくないことが示唆された．

Modelling Motorway Gap Distribution for Evaluating Merging Opportunity of Connected-and-Automated-Vehicles from Dedicated Lanes.

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This study investigates geometric impacts on the gap distributions of Human-Driven-Vehicles (HDVs) to consider locations of exits for dedicated Connected-and-Automated-Vehicle (CAV) lanes, where CAVs must merge into HDVs. For that, the gap distributions are modelled by the combined Gamma distributions for different locations and traffic conditions using Hanshin and Chuo Expressways' data. Based on the estimated model, the required extra time for CAV's merging is hypothetically computed by assuming the random arrival of HDVs on the normal lane at different locations. The result showed that the waiting time tends to increase in a long stretch uphill, suggesting avoiding such locations to locate an exit.

Keywords: *Gap distribution, Time occupancy, Combined model, CAV dedicated lane*

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1. Introduction

1-1 Background

Over the last decade, automated driving technology has been developed rapidly around the world. Connected and Automated Vehicles (CAVs) are expected to boost capacity and minimize congestion by avoiding natural speed reductions induced by road geometry by leveraging vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technology.

At the present stage, CAVs that are partially automated and can-do conditional automation with the intervention of human drivers are in mass production. However, the technology requires further development and time before a CAV can be fully automated. Current CAV technology is not feasible in all cases, even on motorways, which involve motorized traffic only, from the on-ramp or to the off-ramp and under various traffic conditions.

A possible way to early introduce CAVs is by providing dedicated CAV lanes. By analyzing heterogeneous flow models, Ye et al. [1] suggested CAVs can revive their true potentials earlier in dedicated CAV lanes than in heterogeneous traffic flow. Assuming that dedicated CAV lanes are installed on the median side of the motorway, there will be fewer conflicts from vehicles merging from the on-ramp or vehicles diverging to the off-ramps; rightmost lane in case of left-handed traffic in Japan as illustrated in Figure 1. This study considers the exit for dedicated CAV lanes. Even though homogeneous traffic flow can realize smooth and efficient operation inside the dedicated CAV lanes, CAVs must merge into Human-Driven-Vehicles (HDVs) on the normal lane at the exit, influencing both the dedicated CAV and normal lane. Therefore, such an exit's design and operation are critical elements for the dedicated CAV lanes.

1-2 Literature review

Existing studies state that the merging requires a complex combination of merging plan choice, gap acceptance, target gap selection, and acceleration decisions [2] and is also affected by road design and traffic flow [3]. Dülgar et al. [4] have revealed that the merging time threshold, which is the time needed to complete a CAV merge, is a crucial parameter for automated vehicles. By analyzing different gaps of 2, 4, 5 and 6 s, Dülgar et al. [4] concluded that for a safe merging, the minimum critical gap is 4 s.

On the other hand, to understand given conditions for merging CAVs, gap or headway distributions of the HDVs need to be analyzed. These distributions have long been researched as one of the traffic flow characteristics. For example, Zhang et al. [5] considered different headway characteristics under different traffic flow conditions and concluded that the headway distribution shapes are different for different traffic flow levels and time periods. Ha et al. [6] summarized different statistical models, including combined and mixed models that fit the empirical gap distributions.

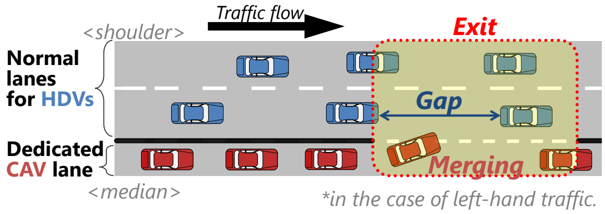

Figure 1 Schematic of a dedicated CAV lane

1-3 Objective

This study attempts to utilize gap distributions of HDVs for evaluating the merging opportunity of CAVs from the dedicated lanes. Here, parameters that determine CAVs' merging performance (i.e., critical gap) are assumed to be given based on the existing research.

The fundamental hypothesis of this study is that gap distributions of HDVs may be affected by road geometry and traffic conditions; this makes the merging opportunity of CAVs different along a motorway section. Therefore, gap distributions are modelled for different locations and traffic conditions and merging opportunities are evaluated under different conditions. This study helps us to discuss preferable/avoidable motorway sections and traffic conditions to locate an exit of the dedicated CAV lanes.

2. Methodology

2-1 Gap distribution modelling

In this study, the gap distribution at any location was modelled using the combined Gamma distribution:

$$f(t) = \varphi * g(t) + (1 - \varphi) * h(t)$$

where both $g(t)$ and $h(t)$ follow Gamma distribution. It can be imagined that there are two types of gaps, the ones of vehicles following their leaders and the others of vehicles not following. Existing studies have shown that the combined Gamma distribution can represent such a characteristic well [7]. The parameters of the distributions

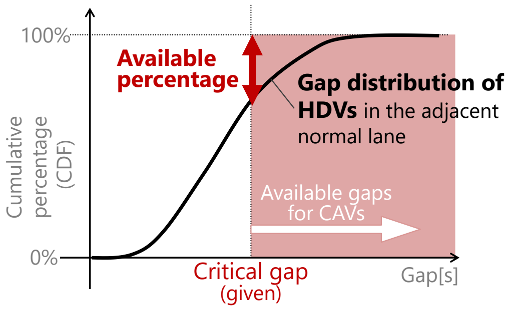

Figure 2 Concept of "available percentage"

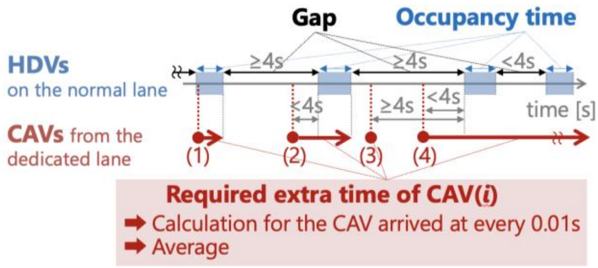

Figure 3 Schematic examples of "required extra time"

were initially set by dividing the gaps into two clusters using k-mean clustering [8] and identified through the maximum likelihood estimation using MATLAB.

The errors between the estimated and observed "available percentage" was calculated to evaluate the models. Here, the smallest gap which allows CAVs from the dedicated lane to merge into HDVs is called a "critical gap". The "available percentage" is the percentage of available gaps that are longer than a "critical gap", as illustrated in Figure 2. In this study, 4 s was assumed for the critical gap of CAV according to Dülgar et al. [4].

2-2 Occupancy time distribution modelling

Occupancy time in this study is defined as the time when a location on the motorway is occupied by vehicle length. CAVs cannot merge during such an occupancy time. In this study, the occupancy time distribution of each location was modelled by a single Gamma distribution.

2-3 Evaluation of merging opportunity

As mentioned above, the available percentage is one of the indices for evaluating the merging opportunity of a CAV in case an exit of the dedicated CAV lane is located at each location along the motorway section. In addition, based on the above-developed models, merging opportunity was evaluated using the "required extra time". This index represents the time duration that a CAV needs, in addition, to merging from the hypothetical dedicated CAV lane into the normal lane of HDVs at the specific location due to the limited arrivals of available gaps (≥ the critical gap). Travelling with acceleration/deceleration of merging CAVs along the continuous locations and merging CAV's queuing is not considered.

The following steps computed the required extra time:

1) The occupancy time of an HDV was randomly extracted from the occupancy time distribution model using inverse transform sampling.
2) Similarly, the gap after the HDV of step 1 was randomly extracted from the gap distribution model.
3) Steps 1 and 2 were repeated for the arrival of 100 HDVs. Thus, an arrival pattern of HDVs was obtained.
4) The required extra time of the CAV can be calculated as the elapsed time from its arrival at the location to the beginning of the gap in which the CAV can merge, namely, greater than the critical gap (4 s in this study). Examples of the required extra time depending on CAV's arrival time are illustrated in Figure 3. Assuming a CAV may arrive at an arbitrary time, the required extra times were calculated by shifting the arrival time of the CAV with 0.01 s. The average of all these cases was taken as the "required extra time".
5) Steps from 1 to 4 were repeated 50 times, and the average of these iterations was taken.

2-4 Study sites and data

Two sites were analyzed for this study. The detailed geometry of these sites is illustrated in Figure 7(a).

Site 1 is in the inbound direction of Route 11 near Tsukamoto junction of Hanshin Expressway, an urban expressway in Osaka. It is a two-lane section with an S-shaped curve, a slight change in gradient, and merging from the on-ramp. Around the on-ramp, lane change is prohibited. The data is from image sensing called "Zen Traffic Data [9]", collected for five different time periods in September 2018.

Site 2 is in the section between Sagamiko and Sagamiko-East interchanges (outbound direction from Tokyo) of Chuo Expressway, an intercity expressway. It is a two-lane section without any on-ramp or off-ramp. The gradient changes along the road section from - 4.5% to 3.5% (sag). Video recording was conducted on two weekdays, 25th and 26th November 2020, from 8.00 a.m. to 4.00 p.m.

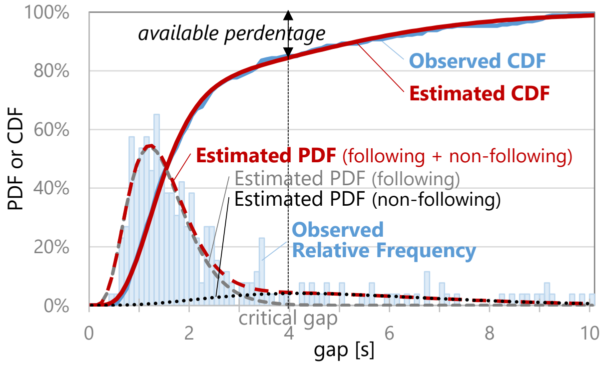

Figure 4 Example of gap distribution

Assuming that the dedicated CAV lanes are usually in the rightmost lane (Figure 1), CAV's merging opportunity is determined by the gaps in the median lane. Therefore, our study examined gaps on the median lane. Because gaps may differ by type of the leading and following vehicles and there were limited samples of large vehicles, gaps where the leading and the following vehicles are small were only analyzed.

It is known that gap distributions are different for different traffic conditions [5]. Therefore, the average velocity and volume were calculated every 5 min for both sites. This paper focuses on the uncongested conditions; the cases with an average velocity greater than 60 km/h in Site 1 and 80 km/h in Site 2 were only analyzed. Traffic volume was classified by every 30 veh/5min, but due to the limited observations, available traffic-volume classes were not completely the same for both sites. The sample size of each class is mostly above 200, not smaller than 100.

3. Results

3-1 Modelling

An example of the combined Gamma distribution gap model (at 43.6 kp in Site 2, 90-120 veh/5min) is shown in Figure 4. Errors in the available percentage, the estimated minus the observed, were within ±2 percentage points, as shown in Figure 5. The error is accounted for less than 20% in percentage errors for most cases, except for the case of 150-180 veh/5min of Site 1 that showed low accuracy. The model showed better accuracy for Site 2 than for Site 1.

φ value in the equation in 2-1, indicating the ratio of vehicles following their leader, tended to increase with the volume, particularly in Site 1, as shown in Figure 7(b).

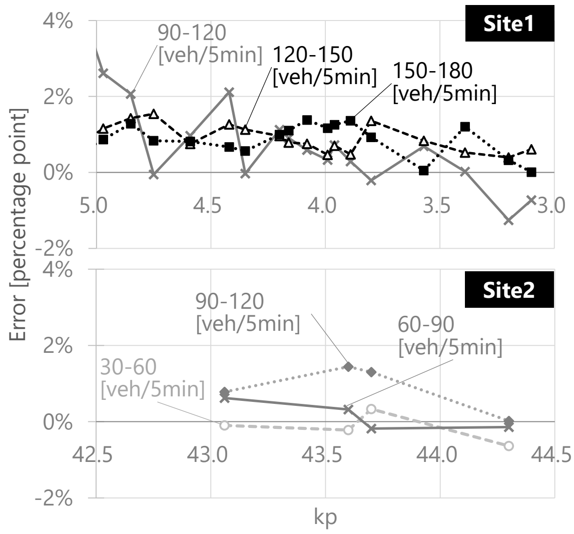

Figure 5 Errors in available percentage

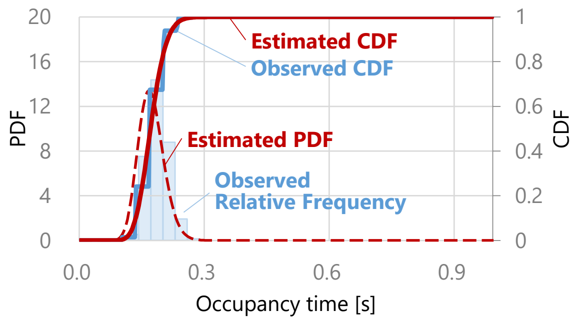

Figure 6 Example of occupancy time distribution

Geometric impacts were not obvious, but the increase of φ from around 4 kp under 90-120 and 120-150 veh/5min in Site 1 might be affected by the change of the gradient from negative to positive. Although the on-ramp at 3.8 kp might also be the cause, lane-changing from the shoulder lane to median lane was less because of the lane change prohibition up to 3.5 kp. These models' shape and scale parameters did not show significant relation with the volume and geometry.

Regarding the time occupancy distribution model, an example for the same case with Figure 4 is shown in Figure 6. It was generally distributed between 0.1-0.4 s.

3-2 Evaluation of merging opportunity

Available percentage and required extra time were shown in Figure 7(c) and (d). The required extra times tended to be longer when the available percentages were small; this is reasonable because a smaller available percentage means fewer opportunities to face a gap greater than the critical gap.

In general, the available percentage decreased with the increase in traffic volume while the required extra time increased. Thus, with higher traffic volume, the dedicated CAV lane might no longer be feasible. An exit should be carefully designed so that CAVs do not fail their merging, for example, by providing an appropriate length of merging lane, V2I technology that monitors and provides the arrivals of HDVs to merging CAVs, etc.

In Site 1, the available percentage decreased, and the required extra time increased under 90-120 veh/5min from around 4.0 kp; this may be due to the impact of gradient change from negative to positive, as also mentioned for φ in 3-1. Another cause might be the illegal lane changing upstream despite the lane change prohibition from 4.2 kp to 3.0kp, which suggests that an exit of the dedicated CAV lane should be avoided in such a section with both change in gradient and a high possibility of lane changing. Under higher volume, the required extra time became constantly long, irrelevant to the gradient.

In Site 2, a decrease in the available percentage and an increase of the required extra time were found in the uphill section under 90-120 veh/5min. Similar to Site 1, this may be an impact of the continuous positive gradient. However, even though the gradient is much steeper in Site 2, the change in the available percentage and required extra time were not more significant than in Site 1. Furthermore, this trend was not seen under lower volume classes, suggesting that merging opportunity is not much influenced by geometry under very light traffic.

4. Future Works

The results from the analysis implied that the impacts of positive gradient on gap distributions depend on the traffic volume conditions, but which could not be strongly confirmed due to the limited observations. For further validation, an investigation by increasing the number of sample sites and traffic conditions is necessary. Interaction of gaps between median and shoulder lane, the impact of on-ramp and off-ramp will also be considered. Furthermore, because the current study evaluated merging opportunities based on simplified indices such as the available percentage and required extra time, the evaluation methodology will be improved by considering the relative velocity between CAVs and HDVs and other parameters.

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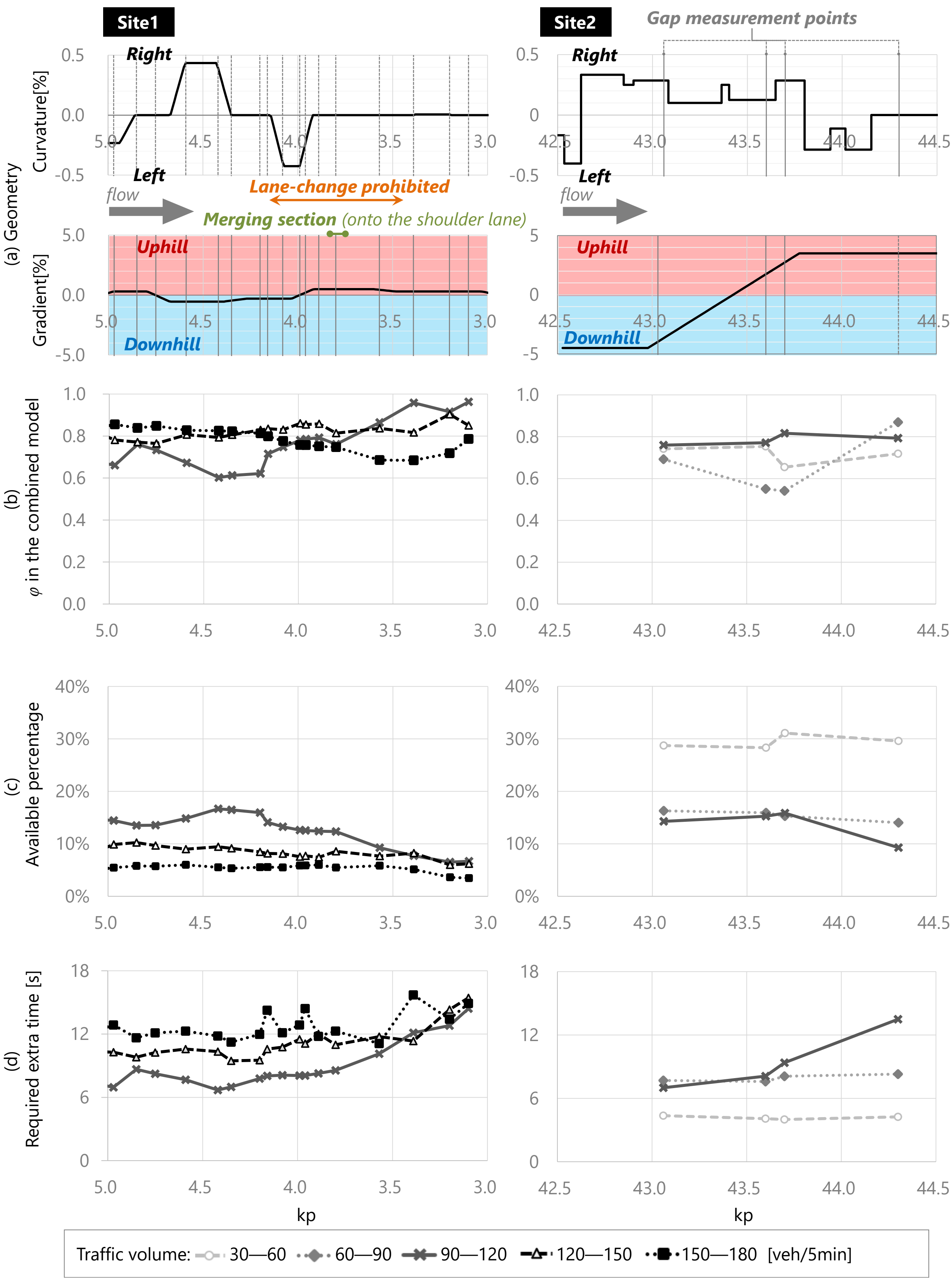

Figure 7 Results of gap distribution modeling, available percentage, and required extra time