Evaluation of Vehicle Position Estimation Method Combining Roadside Vehicle Detector and In-vehicle Sensors

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***Abstract*—Properly managing merging at junction is important in improving highway traffic safety and traffic flow. Accurate vehicle positions and velocities are necessary in realizing proper management, but existing sensors have both advantages and disadvantages. Roadside vehicle detectors are very accurate, but only available at fixed points. By contrast, in-vehicle Global Navigation Satellite System (GNSS) sensors can be used anywhere except in tunnels, but are less accurate. However, these sensors can compensate for each other's week points. In this paper, we propose a vehicle position estimation method that combines road-side vehicle detector and in-vehicle sensors. This method is used to gather data from the roadside vehicle detector and in-vehicle sensors via different wireless networks. It then applies Kalman filters to calculate the accurate position and velocity. When exchanging information over wireless networks, communication delays occur and the data arrival sequence is not guaranteed. Our method can retroactively calculate the vehicle position in the presence of delays below a maximum acceptable threshold. This study evaluates in several simulations using the data created from the GNSS position error and communication delay models. We also perform the evaluation using a dataset created based on the actual vehicle information and communication delays in the simulations. The simulation results show that our method can more accurately estimate the vehicle positions compared to that using data from either sensor alone. Moreover, our method is more suitable for managing traffic and controlling merging at junctions.**

Index Terms*— *Sensor fusion; Position estimation; Communication delays; Intelligent transportation system.

I. Introduction

This paper is an enhanced version of [1]. Vehicles merging into the main lane at highway junctions are increasingly causing the traffic congestion in that lane [2]. Moreover, 20–30% of highway truck accidents occur at or near junctions [3]. Thus, appropriately managing traffic and controlling the merging at junctions are important in improving both highway safety and traffic flow.

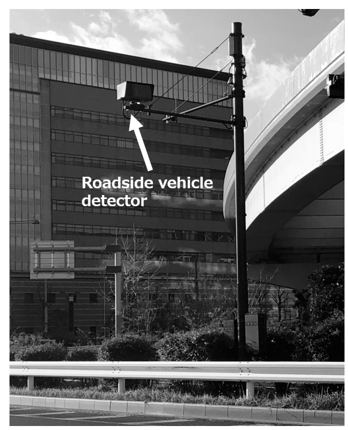

Fig. 1. Roadside vehicle detector.

Fig. 2. General-purpose GNSS sensor.

Several previous studies have investigated proper traffic management and merging control at junctions. Cui et al. [4] proposed a system for detecting collisions by estimating the vehicle arrival time at junctions. Their system obtained the vehicle positions and velocities from a monocular camera

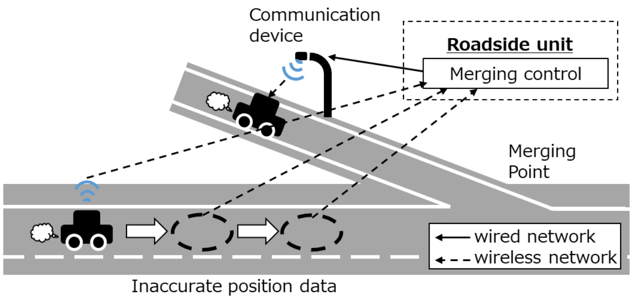

Fig. 3. Existing approach1: using GNSS sensors.

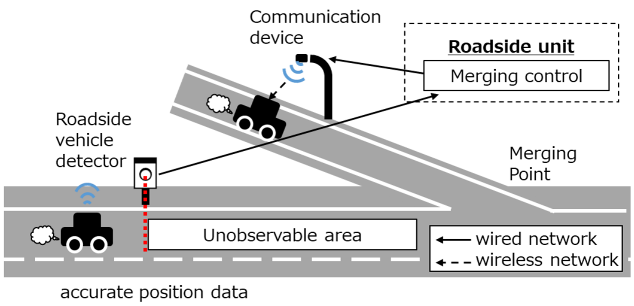

Fig. 4. Existing approach2: using roadside vehicle detector.

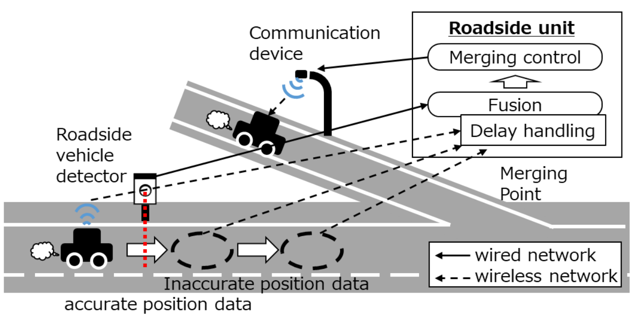

Fig. 5. Proposed approach: combining both sensors.

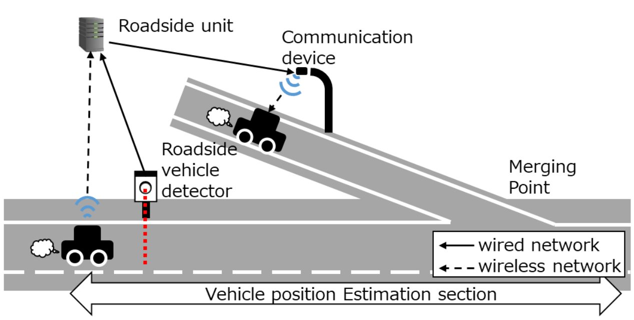

Fig. 6. Merging support system overview.

installed at the junction and used these to estimate the arrival times. Milanes et al. [5] installed a local control system near the junction, which receives the position and velocity information from approaching vehicles and sends them low-risk merging strategies. Chou et al. [6] proposed a merging method based on vehicle-to-vehicle (V2V) communication. The vehicles approaching the junction use this to exchange their positions and velocities. The vehicles in the main lane then create gaps for entering vehicles before they have even reached the merging point. Hirai et al. [7] proposed a system that uses roadside vehicle detector installed before merging points. Roadside vehicle detector are often used to detect the presence of vehicles and the vehicle velocities on the lane to estimate traffic (Figure 1). Hirai's approach was estimated vehicles' arrival times at the merging points. When a vehicle on the on–ramp arrives at almost the same time as a vehicle in the main lane, the system alerts the latter, enabling it to prepare for merging, even if its driver has not seen the vehicle on the on–ramp. Giving drivers longer time to prepare makes the process safe. Japan's government has started field tests of autonomous driving in the Tokyo waterfront area [8]. Accordingly, information on roadside vehicle detector are available in these filed tests. Proper traffic management and merging control at junctions are considered by companies that participated in the field tests.

All the above-mentioned merging methods depend on the vehicle position and velocity information to properly manage traffic and control merging at junctions. The location estimation method using a camera must be applied such that occlusion does not occur, and the place where it can be used is limited. Although accurate vehicle velocities can be obtained from speed sensors, vehicle positions can be incorrect. These are often acquired from position estimation methods using light detection and ranging (LiDAR) or in-vehicle global navigation satellite system (GNSS) sensors. The position estimation method using LiDAR can more accurately estimate the position when compared to GNSS sensors; hence, autonomous vehicles often use it for position estimation. However, the cost of LiDAR usage is much higher than that of using general-purpose GNSS sensors and LiDAR cannot be immediately installed in conventional vehicles. GNSS sensors are obtained position by receiving the signals emitted from satellites and can function anywhere, except in tunnels. The signals received from the satellites contain noise. High-precision GNSS sensors can correct noise [10] and obtain accurate positions, albeit being expensive. The GNSS sensors mounted on vehicles are almost general-purpose products (Figure 2). They are inexpensive, and the positions measured using these sensors can differ from the true position by more than 10 m depending on the location. Properly managing traffic and controlling the merging at junctions cannot be performed with large vehicle position errors [6]. The system using roadside vehicle detector accurately estimates the vehicle arrival times when the sensor is close to the merging point. However, the error increases with the distance between the sensor and the merging point. The establishment cost is also high, and multiple installations are not reasonable because roadside vehicle detector are usually attached to poles installed at roadsides and gates across the road (Figure 1).

Exchanging information via such wireless networks leads to communication delays. Dedicated short-range communications (DSRC) or long-term evolution (LTE) is used for V2V and vehicle-to-infrastructure (V2I) communications. According to

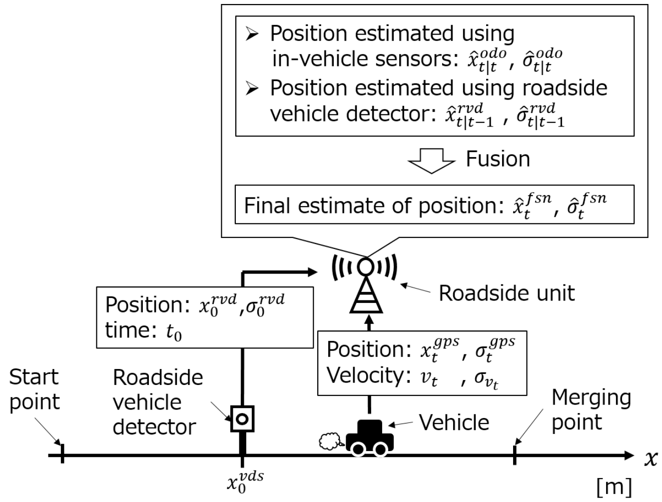

Fig. 7. Illustration of the position estimation model and variable definitions.

Dey et al. [11], these delays are approximately 100 ms for the DSRC (for the communication between a vehicle traveling at 80 km/h and a roadside unit). These delays also mean the data arrival times are not guaranteed. We believe that we can obtain more accurate vehicle positions by combining data from the GNSS and roadside vehicle detectors and compensating for the communication delays.

In this paper, we propose a vehicle position estimation method that combines data from roadside vehicle detector and in-vehicle sensors. This can retroactively calculate prior vehicle positions in the presence of delays below the maximum acceptable threshold. This study makes the following three main contributions.

The first contribution of this study is a vehicle position estimation method that combines data from roadside vehicle detector and in-vehicle sensors. In our system, a roadside vehicle detector is installed before the merging point and a roadside unit is installed near the junction. In-vehicle sensor information is used to estimate its position and velocity. A roadside vehicle detector is also used to estimate the vehicle position based on the sensor position and vehicle velocity. The two estimates are combined using a statistical approach proposed by Duffin [12]. Previous studies used only one of the position information obtained from the GNSS and roadside vehicle detector (Figures 3 and 4). Our method estimates positions using both position information (Figure 5).

The second contribution of this study is a communication delays compensation method. The vehicle positions at earlier times are retroactively calculated when older data arrive up to the predetermined maximum communication delay. When the roadside unit does not receive information from a vehicle, it estimates the vehicle's position based on the most recent information received from it. Modified Kalman filters that consider communication delays are proposed [14]. The contribution is applying the modified Kalman filters to the scene of merging support.

The third contribution of this study is the evaluation of our system. We evaluated our proposed system by using only the data created from the GNSS position error and communication delay models in several simulations [1]. In this paper, our system was also evaluated by using a dataset created based on actual vehicle information and communication delays in simulations. The actual vehicle information were obtained when driving through a main lane of the airport west interchange in Tokyo, Japan. The dataset including communication delays was created by actually transmitting from a certain terminal to other terminal via LTE communication.

The remainder of this paper is organized as follows. Section II describes the assumptions made herein. Section III introduces our proposed system. Section IV evaluates the method using several simulations. Section V presents the results. Section VI discusses our proposed system, and Section VII concludes the paper.

II. Assumption

In this study, roadside vehicle detector were installed before the merging point. A roadside unit was located near the junction (Figure 6). All vehicles are assumed to have GNSS devices, speed sensors, and V2I communication devices. Vehicles approaching the junction send their current position and velocity, as well as the time the data were acquired, to the roadside unit. This information is repeatedly sent at regular intervals in vehicle position estimation section and starts to send before the vehicle passes through the roadside vehicle detector. The system clocks in the vehicles, roadside vehicle detector, and roadside units are assumed to be synchronized. Some delay exists in the communications between the vehicles and the roadside units. Meanwhile, the communication delays between the roadside vehicle detector and the roadside unit are assumed to be negligible because the communication between them is via wire and dedicated connection.

Figure 7 shows the environmental model, where the vehicle drives from the starting point toward the merging point. A roadside vehicle detector is installed at $x = x^{rvd}_0$ m. The vehicle sends information about its position (namely the average x^{gps}_t m and the standard deviation σ^{gps}_t m) and velocity (average v_t km/h and standard deviation σ_{v_t} km/h) to the roadside unit. The roadside vehicle detector sends the position of the vehicle's center (average x^{rvd}_0 m and standard deviation σ^{rvd}_0 m) and the detection time t_0 s to the roadside unit when the vehicle passes through it.

The roadside unit estimates the vehicle's position using both the information received from the vehicle (the average $\hat{x}^{odo}_{t|t}$ m and standard deviation $\hat{\sigma}^{odo}_{t|t}$ m) and that from the roadside vehicular detector (average $\hat{x}^{rvd}_{t|t-1}$ ms and standard deviation $\hat{\sigma}^{rvd}_{t|t-1}$ m). It then combines these two estimates to obtain the final vehicle position (average $\hat{x}^{fsn}_t$ m and standard deviation $\hat{\sigma}^{fsn}_t$ m).

The assumptions in this study are according to the actual field test of Japan [8]. Support for autonomous driving by providing information for automatically adjusting the speed and timing of entering the main line at highway junctions has been considered in the field tests [13]. The experiment has been conducted at an airport west interchange in Tokyo, Japan. Figure 8 shows the top view of the airport west interchange and the sensor location. Figures 9 and 10 illustrate the devices for merging control. Figure 11 depicts the merging point of the airport west interchange. The roadside vehicle detector detects the speed of the vehicles driving on the main lane and sends them to the roadside unit located near the merging point via wire and dedicated connection. The roadside unit estimates the speed and timing to safely join the main lane. These information are provided to the vehicles driving on the ramp via wireless at the place where the communication device is installed. Furthermore, previous studies have already discussed time synchronization [9]. Therefore, these assumptions are realistic.

III. Proposed system

In this section, we describe our proposed position estimation approach, followed by our method of compensating for the communication delays.

A. Position Estimation

Figure 12 presents a flow diagram showing the steps performed to estimate the vehicle position when it passes through the gate at time t_0 s. Here, the vehicle position is estimated by applying Kalman filters to the position and velocity information received from it until it passes through the roadside vehicle detector. Kalman filters are often used to estimate the exact state based on inaccurate and noisy information; hence, we used them here to estimate the vehicle position from the noisy position and velocity information.

The Kalman filters usage is divided into the prediction and correction steps. During the prediction step, the vehicle position is estimated based on the estimate from the previous time step and the current vehicle velocity information. The correction step adjusts this estimated position using the current vehicle position information. The specific equations are presented below.

Prediction step:

$$\hat{x}^{odo}_{t|t-1} = \hat{x}^{odo}_{t-1|t-1} + \frac{5}{18} v_t dt, \tag{1}$$

$$\left(\hat{\sigma}^{odo}_{t|t-1}\right)^2 = \left(\hat{\sigma}^{odo}_{t-1|t-1}\right)^2 + \left(\frac{5}{18}\sigma_{v_t} dt\right)^2. \tag{2}$$

Correction step:

$$\hat{x}^{odo}_{t|t} = \hat{x}^{odo}_{t|t-1} + k_t \left(x^{gps}_t - \hat{x}^{odo}_{t|t-1}\right), \tag{3}$$

$$\left(\hat{\sigma}^{odo}_{t|t}\right)^2 = (1 - k_t)\left(\hat{\sigma}^{odo}_{t|t-1}\right)^2, \tag{4}$$

$$k_t = \frac{\left(\hat{\sigma}^{odo}_{t|t-1}\right)^2}{\left\{\left(\hat{\sigma}^{odo}_{t|t-1}\right)^2 + \left(\sigma^{gps}_t\right)^2\right\}}. \tag{5}$$

where $\hat{x}^{odo}_{t|t-1}$ m and $\hat{\sigma}^{odo}_{t|t-1}$ m are the average and standard deviation of the vehicle position, respectively, generated by the prediction step for timestep t s; $\hat{x}^{odo}_{t|t}$ m and $\hat{\sigma}^{odo}_{t|t}$ m are the average and standard deviation of the vehicle position, respectively, generated by the correction step for timestep t s; v_t km/h and σ_{v_t} km/h are the average and standard deviation of the vehicle velocity, respectively, generated by the correction step for timestep t s; k_t is the Kalman gain at timestep t s; and $\frac{5}{18}$ is a term used for converting the vehicle velocity from

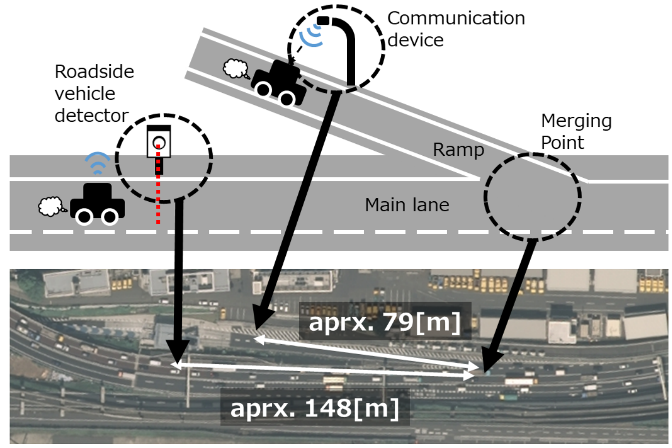

Fig. 8. Status of devices for merging support system at the airport west interchange in Tokyo.

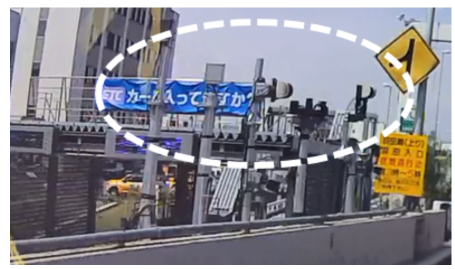

Fig. 9. Roadside vehicle detector.

Fig. 10. Communication device.

Fig. 11. Merging point.

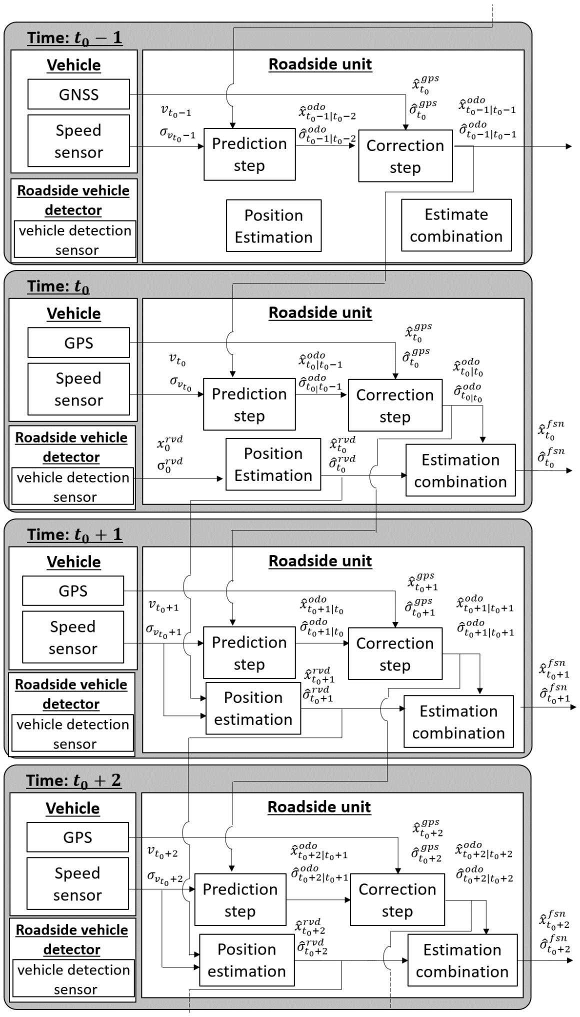

Fig. 12. Flow diagram showing the steps performed to estimate the vehicle position.

km/h to m/s.

The roadside unit receives the position of the vehicle's center from the roadside vehicle detector at time t_0 s, then combines this with the velocity information received from the vehicle and the Kalman filters' prediction step to estimate the vehicle position. The specific equations are presented below.

Position estimation:

$$\hat{x}_t^{rvd} = \hat{x}_{t-1}^{rvd} + \frac{5}{18} v_t dt, \tag{6}$$

$$\left(\hat{\sigma}_t^{rvd}\right)^2 = \left(\hat{\sigma}_{t-1}^{rvd}\right)^2 + \left(\frac{5}{18}\sigma_{v_t} dt\right)^2. \tag{7}$$

where, $\hat{x}_t^{rvd}$ m and $\hat{\sigma}_t^{rvd}$ m are the average and standard deviation of the vehicle position predicted by the Kalman filters at timestep t s, respectively; v_t km/h and σ_{v_t} km/h are the average and standard deviation of the vehicle velocity at timestep t s; and $\frac{5}{18}$ is a term used for converting a vehicle velocity from km/h to m/s.

The vehicle position (average $\hat{x}_{t_0}^{rvd}$ m and standard deviation $\hat{\sigma}_{t_0}^{rvd}$ m) at timestep t_0 s is defined as the position received

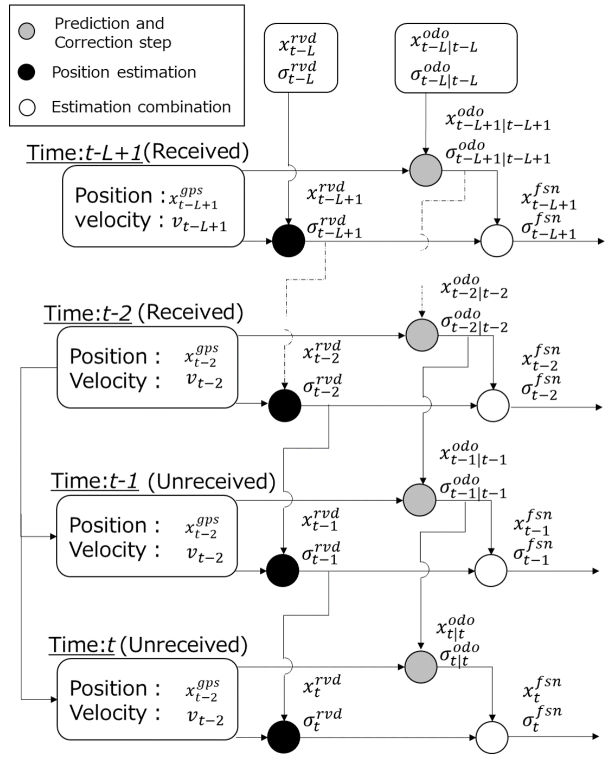

Fig. 13. Overview of our communication delays compensation method.

from the roadside vehicle detector; hence, it is given as follows:

$$\hat{x}_{t_0}^{rvd} = x_0^{rvd}, \tag{8}$$

$$\hat{\sigma}_{t_0}^{rvd} = \sigma_0^{rvd}. \tag{9}$$

where x_0^{rvd} m and σ_0^{rvd} m are the average and standard deviation, respectively, of the vehicle position received from the roadside vehicle detector.

Finally, the two vehicle position estimates are combined using the statistical approach proposed by Duffin [12], which is based on Bayes' rule and Kalman filters. This approach simply combines the two Gaussian distribution.

Estimate combination:

$$\hat{x}_t^{fsn} = \hat{x}_{t|t}^{odo} + \frac{\left(\hat{\sigma}_{t|t}^{odo}\right)^2}{\left(\hat{\sigma}_{t|t}^{odo}\right)^2 + \left(\hat{\sigma}_t^{rvd}\right)^2}\left(\hat{x}_t^{rvd} - \hat{x}_{t|t}^{odo}\right), \tag{10}$$

$$\left(\hat{\sigma}_t^{fsn}\right)^2 = \left\{1 - \frac{\left(\hat{\sigma}_{t|t}^{odo}\right)^2}{\left(\hat{\sigma}_{t|t}^{odo}\right)^2 + \left(\hat{\sigma}_t^{rvd}\right)^2}\right\}\left(\hat{\sigma}_{t|t}^{odo}\right)^2. \tag{11}$$

where, $\hat{x}_t^{fsn}$ m and $\hat{\sigma}_t^{fsn}$ m are the average and standard deviation of the vehicle position obtained by combining the two estimates.

B. Communication delay compensation

Communication delays inevitably occur when exchanging information over wireless networks; thus, they must be considered when estimating the vehicle positions. Here, we used

Kagami et al.'s approach, which involves modified Kalman filters that account for the communication delays [14]. This method retroactively calculates prior positions and velocities when older data are received up to a predetermined maximum communication delay. However, the modified Kalman filters model proposed by Kagami et al. is a multidimensional state–space model. Hence, in this study, the communication delay compensation is only used a concept, and the Kalman filters model is changed to a one-dimensional (1D) constant velocity (CV) model.

Figure 13 illustrates our method of communication delay compensation. Here, L s is the maximum communication delay. $t-L$ s denotes the L timesteps after the vehicle passed through the roadside vehicle detector. The roadside units did not receive any position and velocity information from the vehicle at timesteps $t-1$ and t s. The data is received at timestep $t-2$ s, and the roadside unit uses this to retroactively calculate the vehicle positions and velocities at timesteps $t-1$ and t s, working back from the present time to the predetermined maximum communication delay.

The vehicle position is estimated using Eqs. (1)–(11) at each time. The vehicle position is estimated based on the estimate from the previous time step and each time vehicle position and velocity information. Finally, the two vehicle position estimates are combined.

IV. Evaluation experiments

Our vehicle position estimation method is evaluated in several simulations in this section. First, our vehicle position estimation method is evaluated using the data created from the GNSS position error models and the communication delay model and conducted with and without communication delays. Next, our system is evaluated using a dataset created based on the actual vehicle information and communication delays in the simulations. We used Matlab R2019a herein. Table I shows the personal computer (PC) specifications used for the simulation.

A. Evaluation using models

1) Environment without communication delays: In this experiment, the position estimation accuracy was evaluated in an environment where the communication delays were assumed to be negligible. Our proposed method labeled as "Fusion" was compared with one that simply applies Kalman filters to the in-vehicle sensor data (i.e., "GNSS only").

In this simulation, a vehicle drove from the starting point at $x = -100$ m toward the merging point at a speed of 80 km/h. The roadside vehicle detector was installed at $x = 0$ m. The standard deviations of the vehicle's center position and velocity were set to s $\sigma_0^{rvd} = 0.5$ m and $\sigma_{v_t} = 5$ km/h, respectively. The vehicle sent its position and velocity to the roadside unit every 100 ms. The roadside unit also estimated the vehicle position every 100 ms. The vehicle acquired its position from a GNSS device. We considered two models of the GNSS position error, namely a Gaussian white noise model and a Gauss-Markov random process model, used in a previous study [6]. These models will be described below. The simulation was repeated six times for each GNSS position error model.

TABLE I
SPECIFICATIONS OF THE PC USED FOR THE SIMULATIONS.

CPU	Intel Core i9-9900X at 3.50GHz
Memory	64 GB
Storage	Samsung MZVLB1T0HALR-00000

TABLE II
PARAMETERS OF THE GAUSSIAN WHITE NOISE MODEL.

GNSS error	σ_w
Low	3
Medium	6
High	9

TABLE III
PARAMETERS OF THE GAUSS–MARKOV RANDOM PROCESS MODEL.

	σ_g	σ_r	β
Case 1	0.2020	0.0027	1/600
Case 2	0.1030	0.3160	1/600

Gaussian white noise model:
This is given by the following equations:

$$x_t^{gps} = x_t + w_t. \tag{12}$$

where, x_t is the actual vehicle position, and w_t is the Gaussian white noise, i.e., $w_t \sim N(0, \sigma_w)$. Here σ_w is set as in Table II. σ_w in Table II is set from a trial experiment using a general-purpose GNSS sensor. UBX-M8030-KT was used for a general-purpose GNSS sensor. The specifications of it denotes in Table IV. When position data were acquired using the sensor at multiple points in Nagoya University, the most low value was $\sigma_w \approx 3$, the most high value was $\sigma_w \approx 9$. Thus the σ_w is set as 3 in the low GNSS error and the σ_w is set as 9 in the high GNSS error. As an intermediate value between the high and low GNSS error, σ_w is set as 6 in the medium GNSS error.

Gauss–Markov random process model:
This is given by the following equations [15]:

$$m_t = e^{-\beta dt} m_{t-1} + g_t, \tag{13}$$

$$n_t = m_t + r_t, \tag{14}$$

$$x_t^{gps} = x_t + 0.9 n_t. \tag{15}$$

Here, represents time–correlated noise with time constant β and Gaussian white noise g_t, i.e., $g_t \sim N(0, \sigma_g)$. In addition, n_t is the total noise composed of m_t and uncorrelated noise r_t, i.e., $r_t \sim N(0, \sigma_r)$. As in the previous study [6], σ_g, σ_r, and β were set as in Table III. The GNSS error in Case 2 was worse than that of Case 1.

2) Environment with communication delays: In this experiment, our communication delay compensation method was evaluated by comparing the performance our method, called "Fusion with DC" with those of the other two methods.

The first method (i.e., "GNSS only without DC") estimated the vehicle position by applying Kalman filters to the in-vehicle sensor data without compensating for the communication delays. This method only used the most recent position

TABLE IV
SPECIFICATIONS OF THE GNSS SENSORS USED IN THE EXPERIMENT.

AQLOC-VCX (Mitsubishi Electric)	
Receiver type	GPS, QZSS, Galileo
Horizontal position accuracy	12.0 cm
Internal antenna	Dielectric antenna (59x59x33 mm)
UBX-M8030-KT (u-blox)	
Receiver type	GPS, QZSS, GLONASS
Horizontal position accuracy	2.0 m
Internal antenna	Dielectric antenna (25x25x4 mm)

and velocity information received, thereby ignoring older delayed data. The second method (i.e., "GNSS only with DC") was similar, but with communication delay compensation.

In this method, the communication delays were represented by a Gaussian white noise (i.e., $N(\bar{d}, \sigma_{\bar{d}}^2)$ $\bar{d}$ was set to 96.130 ms following that in a previous study [11], and $\sigma_{\bar{d}}$ was set to 2 ms). We considered three possible maximum communication delays, namely 0.10, 0.12, and 0.14 s, and repeated each simulation six times.

B. Evaluation using actual data

In this experiment, the proposed system was also evaluated using a dataset created based on actual vehicle information and communication delays. The actual vehicle information were obtained when driving through a main lane of the airport west interchange in Tokyo, Japan. The dataset, including the communication delays, was created by actual transmission from a certain terminal to the other terminal via LTE communication. Accordingly, the performance of our proposed method ("Fusion") was compared with those of the other three methods. The first method ("RVDS only") estimated the vehicle position by applying a linear uniform motion to the time and speed, at which the vehicle passed the roadside vehicle detector. The second method ("GNSS only with CD") estimated the vehicle position by applying Kalman filters to the in-vehicle sensor data with communication delay compensation. The third method ("GNSS only without CD") estimated the vehicle position by applying Kalman filters to the in-vehicle sensor data without communication delay compensation. In this simulation, the standard deviation of the vehicle's center position, vehicle position, and velocity were set to s $\sigma_0^{rvd} = 0.5$ m, $\sigma_0^{gps} = 2$ m, and $\sigma_{v_t} = 5$ km/h, respectively. The vehicle sent its position and velocity to the roadside unit every 100 ms, and the roadside unit estimated the vehicle position every 100 ms.

1) Acquisition of vehicle information: The vehicle position and velocity were acquired using two sensors. Table IV lists the sensor specifications. AQLOC-VCX is a high-precision GNSS sensor that can acquire quasi-zenith satellites information. This sensor includes an IMU and can obtain the vehicle position and velocity by inputting the vehicle speed pulse and the back pulse. Therefore, the position information obtained from it were used as the correct vehicle position data,while the velocity information were used for the position estimation. UBX-M8030-KT is a general-purpose GNSS sensor. The position information obtained from it were used herein for the position estimation. These sensors were mounted on the vehicle celling (Figure 14).

Fig. 14. Experimental vehicle and sensor installation.

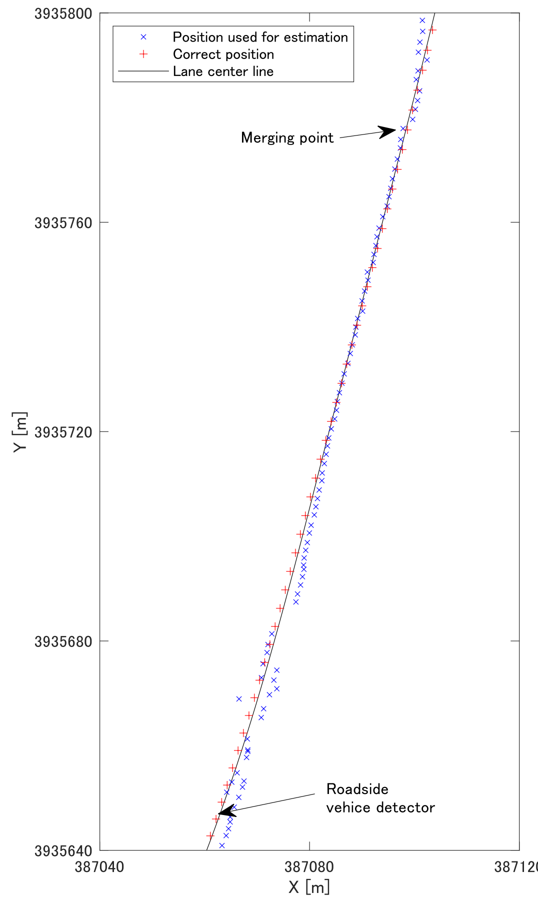

Fig. 15. Vehicle position acquired by GNSS sensors.

Figure 15 shows the vehicle position acquired by the GNSS sensors. The vehicle position was expressed in the UTM coordinate system. The lane center line was extracted from a high-precision map created using the mobile mapping system. The correct vehicle position was along the lane center line. Meanwhile, the position used for the estimation was far from the lane center line because of noise.

Our proposed position estimation method used a 1D CV model and considered lateral movement, but not vertical movement. The position information of the GNSS outputs were 2D. In this simulation, the position information were projected to the lane center line, and we only considered the lateral movement. Figure 16 shows how the position error changed

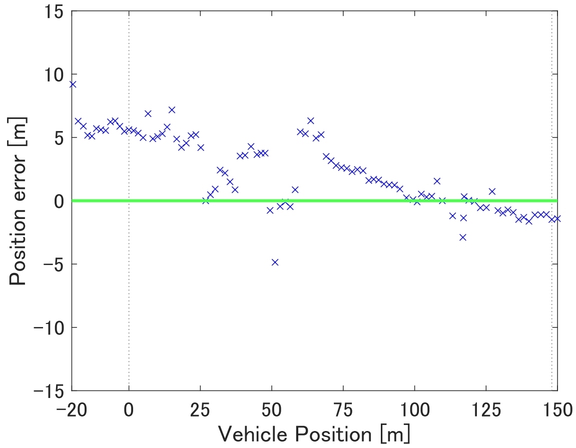

Fig. 16. Position error versus true position.

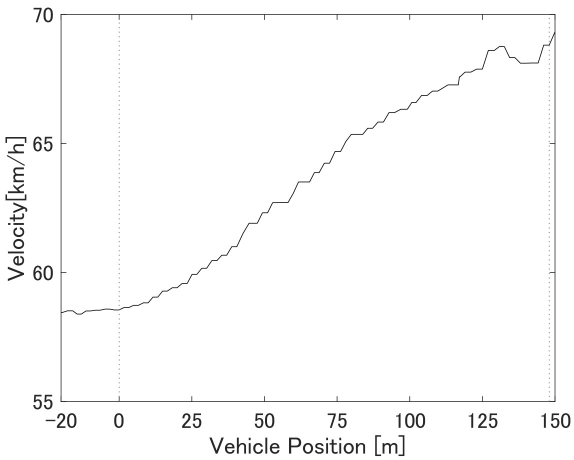

Fig. 17. Vehicle velocity versus true position.

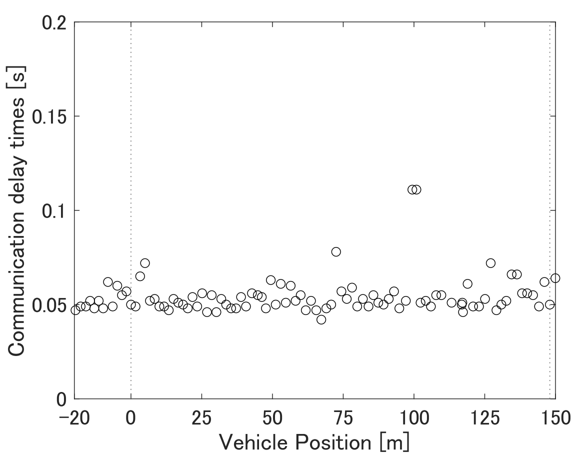

Fig. 18. Communication delay times versus true position.

with the vehicle position. The roadside vehicle detector was installed at $x = 0$ m. The merging point was at $x = 148$ m. The vehicle estimation section started from $x = -20$ m to $x = 150$ m. The horizontal axis represents the position, whereas the vertical axis represents the position error, namely the difference between the correct vehicle position and the vehicle position used for estimation. When the position error was positive (negative), the vehicle's estimated position was ahead (behind) its true position. The vehicle position used for the estimation had a large position error near the roadside vehicle detector and a small position error near the merging point.

Figure 17 exhibits how the vehicle velocity changed. The horizontal axis represents the true vehicle position, whereas the vertical axis represents the vehicle velocity at that position. The vehicle accelerated from the roadside vehicle detector toward the merging point.

2) Addition of communication delays: The information obtained from the GNSS sensors did not include communication delays. To contain the actual communication delays, the vehicle information were transmitted between the terminals that were time synchronized using the ntp server via LTE communication. The communication delays were then recorded. The communication carrier used in the experiments was b-mobile, mobile virtual network operator of Docomo. Docomo is the main communication carrier in Japan.

Figure 18 represents the state of the communication delays. The horizontal axis represents the actual vehicle position, whereas the vertical axis represents the communication delay times. The average value of the communication delays were approximately 0.05 s. The maximum value is 0.111 s, whereas the minimum value was 0.042 s. Therefore, the maximum communication delay time was set to 0.12 s in this experiment.

V. RESULTS

A. Evaluation using models

1) Environment without communication delays: Table V presents the simulation results. Figures 19-23 show how the position error changed with the vehicle position. The horizontal axis represents the true vehicle position, while the vertical axis represents the position error, namely the difference between the true and estimated vehicle positions. When the position error was positive (negative), the vehicle's estimated position was ahead (behind) its true position.

Table V shows that the average and standard deviation of the position error were both lower for "Fusion" than for "GNSS only." When the vehicle passed through the roadside vehicle detector, the position error of the "Fusion" method sharply dropped, becoming much lower than that of the "GNSS only" (Figures 19-23). This result demonstrates that the proposed position estimation method can be significantly more accurate than "GNSS only."

2) Environment with communication delays: Table VI shows the simulation results. Figures 24-26 depict how the position error changed with the vehicle position. The horizontal axis represents the true vehicle positions, whereas the vertical axis represents the position error defined as before.

Table VI shows that both the average and standard deviation of the position error were lower for our "Fusion with DC" method compared to the other approaches. The errors were lower for the "GNSS only with DC" than for the "GNSS only without DC" and significantly lower for "Fusion with DC" than for the other methods when the maximum communication

TABLE V
COMPARISON OF POSITION ESTIMATION METHODS.

Gaussian white noise model (Low GNSS position error)	Average	Standard deviation
GNSS only	0.298 m	0.182 m
Fusion	0.238 m	0.030 m
Gaussian white noise model (Medium GNSS position error)	**Average**	**Standard deviation**
GNSS only	0.360 m	0.290 m
Fusion	0.260 m	0.052 m
Gaussian white noise model (High GNSS position error)	**Average**	**Standard deviation**
GNSS only	0.467 m	0.461 m
Fusion	0.274 m	0.085 m
Gauss–Markov random process model (Case 1)	**Average**	**Standard deviation**
GNSS only	1.681 m	0.907 m
Fusion	1.280 m	0.591 m
Gauss–Markov random process model (Case 2)	**Average**	**Standard deviation**
GNSS only	0.691 m	0.467 m
Fusion	0.477 m	0.315 m

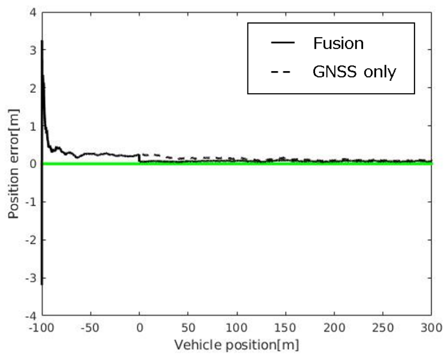

Fig. 19. Position error versus true position (Gaussian white noise model with a low GNSS position error).

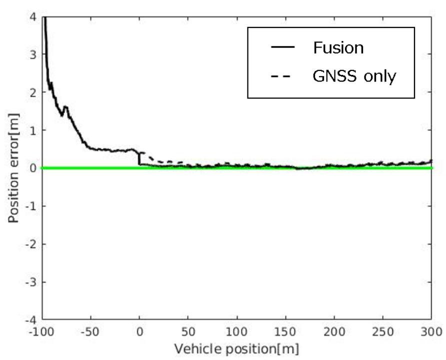

Fig. 20. Position error versus true position (Gaussian white noise model with a medium GNSS position error).

delay time was 0.14 s. We believe this was because the amount of data that had to be discarded due to not being received within the maximum communication delay time decreased as the maximum communication delay time increased.

Figures 24-26 depict that the position error was always negative for the “GNSS only without DC” method because the latest information received from the vehicle was out-of-data due to communication delays. The fact that the errors

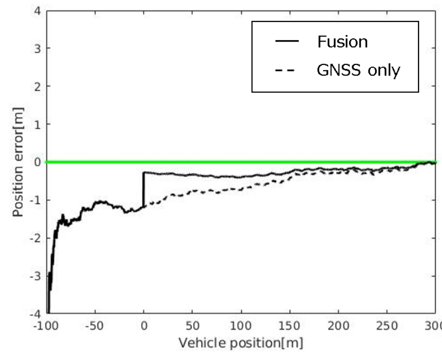

Fig. 21. Position error versus true position (Gaussian white noise model with a high GNSS position error).

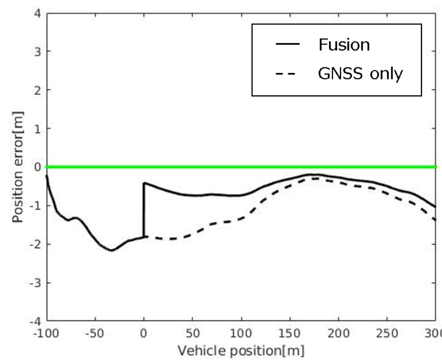

Fig. 22. Position error versus true position (Gauss-Markov random process model, Case 1).

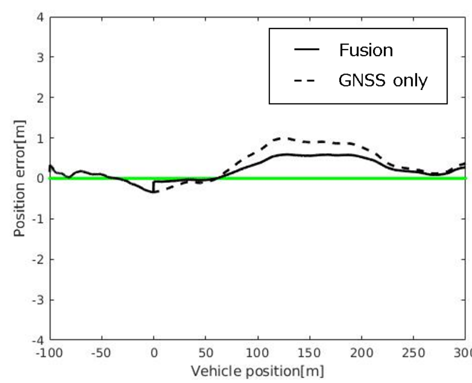

Fig. 23. Position error versus true position (Gauss-Markov random process model, Case 2).

were smaller for both “GNSS only with DC” and “Fusion with DC” confirmed that our communication delay compensation method performed well. In addition, the fact that the position errors were lower for our “Fusion with DC” method than for “GNSS only with DC” confirmed that our proposed method can more accurately estimate the vehicle position than “GNSS only” in an environment with communication delays.

B. Evaluation using actual data

Table VII lists the simulation results. Figure 27 shows how the position error changed with the vehicle position. Table VII

TABLE VI
EVALUATION OF OUR COMMUNICATION DELAYS COMPENSATION METHODS.

	Average	Standard deviation
GNSS only without DC	-2.420 m	0.612 m
Maximum communication delay of 0.10 s	Average	Standard deviation
GNSS only with DC	-0.471 m	0.527 m
Fusion with DC	-0.248 m	0.065 m
Maximum communication delay of 0.12 s	Average	Standard deviation
GNSS only with DC	-0.410 m	0.411 m
Fusion with DC	-0.246 m	0.059 m
Maximum communication delay of 0.14 s	Average	Standard deviation
GNSS only with DC	-0.380 m	0.362 m
Fusion with DC	-0.234 m	0.063 m

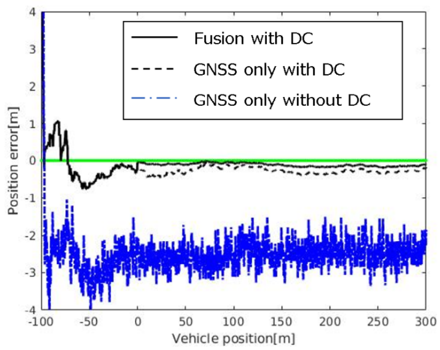

Fig. 24. Evaluation of our communication delay compensation method (maximum communication delay of 0.10s).

TABLE VII
COMPARISON OF POSITION ESTIMATION METHODS.

	Position error at the merging point	Average	Standard deviation
Fusion	-1.037 m	0.576 m	1.707 m
RVDS only	-14.420 m	-8.035 m	6.722 m
GNSS only with DC	-0.862 m	2.181 m	2.840 m
GNSS only without DC	-2.513 m	0.468 m	2.889 m

summarizes the position error at the merging point, and the average values and standard deviation of the position errors after passing the roadside vehicle detector until reaching the merging points. The horizontal axis represents the true vehicle position, whereas the vertical axis represents the position error, namely the difference between the true and estimated vehicle positions. The vehicle's estimated position was ahead (behind) its true position when the position error was positive (negative).

Table VII shows that "GNSS only with DC" method had the smallest position error at the merging point. The position estimation method with the smallest average value was "GNSS only without DC," and the method with the smallest standard value was "Fusion." The value of "RVDS only" was large in all items.

Figure 27 also depicts that the position errors of "Fusion" and "RVDS only" were very small when the vehicle passed through the roadside vehicle detector and the position can accurately be obtained. The positon error of "RVDS only" gradually left behind its true position because the vehicle

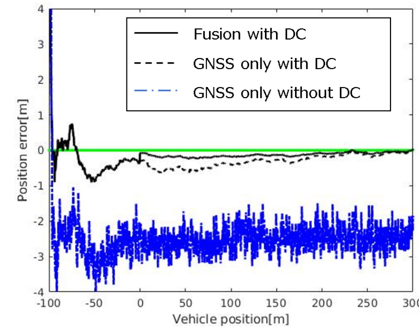

Fig. 25. Evaluation of our communication delay compensation method (maximum communication delay of 0.12s).

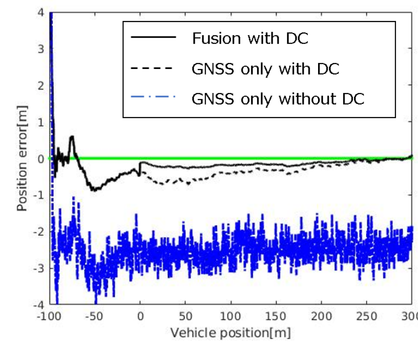

Fig. 26. Evaluation of our communication delay compensation method (maximum communication delay of 0.14s).

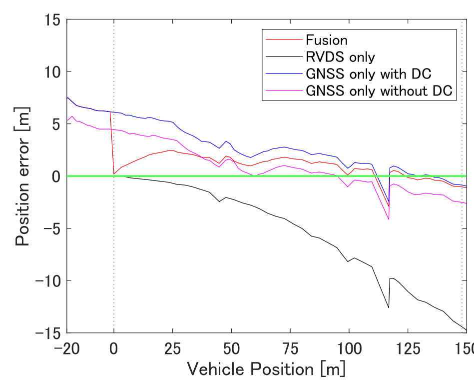

Fig. 27. Position error versus true position.

accelerated after passing through the roadside vehicle detector (Figure 17). Finally, the fact that the estimated position were always behind for the "GNSS only with DC" method than for the "GNSS only without DC" method confirmed that our communication delay compensation method performed well.

VI. Discussion

This section discusses the advantage of the proposed method based on the evaluation results.

A. Advantages of the proposed method

The position estimation using only the roadside vehicle detector information can accurately estimate the vehicle position near the roadside vehicle detector. However, an accurate position estimation cannot be performed when the vehicle velocity changes after passing the roadside vehicle detector. Vehicle velocity changes often occur to deal with vehicles merging into the main lane; thus, vehicle speed information are necessary for an accurate position estimation. In this respect, the proposed method and the position estimation method using only the in-vehicle sensors have an advantage.

Merging support systems create merging support information based on the position information of the vehicles approaching the merging point. Therefore, the position information near the merging point are more important for the merging support system than at the merging point. Furthermore, the merging support system may provide strange merging support information if the standard deviation is large, even if the average of the position error is small after passing the roadside vehicle detector until reaching the merging points. Thus, the average and standard deviation of the position error must be small after passing the roadside vehicle detector until reaching the merging points. The evaluation experiment confirmed that the proposed method can accurately estimate the vehicle position near the roadside vehicle detector because of the information from the roadside vehicle detector. Consequently, we confirmed that the average and standard deviation of the position error after passing the roadside vehicle detector until reaching the merging points become relatively small. Therefore, the proposed method has an advantage over the position estimation method using only in-vehicle sensor information in terms of support system reliability.

The method without the communication delay compensation estimates the position based on the past information of the GNSS due to the communication delays. The evaluation experiment showed that the estimated position was always behind the position estimated using the method with the communication delay compensation. Thus, communication delay compensation is useful in the environment with communication delays.

B. Maximum communication delay time

In the evaluation using the actual data, we set the maximum communication delay time based on the record of the communication delay times. Communication delays are influenced by various factors, such as the number of vehicles and building. The time required for the position estimation increases as the maximum communication delay time increases. The maximum communication delay time must be set considering the time constrain of the merging support system and the communication delay time in various situations.

VII. Conclusion

In this study, our system was evaluated in several simulations using the various models and actual data. We demonstrated that the proposed method can estimate vehicle positions more accurately than that using only the in-vehicle sensors and roadside vehicle detector. We also confirmed that our communication delay compensation method can perform well. Our method can estimate the vehicle positions accurately in environments with communication delays; hence, it is more suitable for managing traffic and controlling merging at junctions.

We will explore several topics in the future work. The proposed method can be applied while the delay occurs according to a specific distribution. The communication delay distribution tendency drastically changes with the number of increasing vehicles. Thus, a method that can handle it, even if the communication delay distribution tendency is changed, must be considered. We would like to evaluate whether or not the proposed method works correctly by incorporating it into the merging support system proposed in the previous research.

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