Cooperative Adaptive Cruise Control System Identification in Multi-brand Truck Platooning

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Abstract

This study examines the identification and evaluation of Cooperative Adaptive Cruise Control (CACC) systems created by four major Japanese truck manufacturers, focusing on data gathered from real-world platooning experiments. Utilizing information from a 2019 multi-vehicle field test, we identified CACC control rules by differentiating between acceleration and deceleration phases and implementing constrained linear least-squares estimation. The resulting models accurately replicated the commanded acceleration profiles for each manufacturer's system with high fidelity. We verified the validity of these models through simulations using TruckMaker and Simulink, which showed that they aligned with experimental vehicle speed responses and effectively reproduced dynamic behaviors. To evaluate operational performance in multi-brand platooning scenarios, we conducted simulations that varied platoon order, deceleration levels, and target time headways. The results identified specific platoon configurations that exhibited decreased gap-keeping stability, indicating that high deceleration or short time headways could negatively affect performance. To enhance this performance, we proposed a control strategy that uses the desired acceleration of the lead vehicle as a feedforward input. Compared to traditional CACC, this proposed method significantly decreased settling time and jerk, particularly during emergency braking conditions, where responsiveness was greatly improved. These findings contribute to the advancement of practical and robust CACC systems for multi-brand truck platooning and lay a foundation for their early implementation in real-world freight logistics.

Keywords Cooperative Adaptive Cruise Control, Heavy-duty Truck, Platooning, Autonomous driving, Simulation

1 Introduction

The Japanese transportation sector is currently facing several critical social issues [1], including environmental concerns, energy challenges, and driver shortages. The growing anticipation is that large-truck platooning may provide solutions to these problems.

As part of the Energy ITS Promotion Project [2][3], initiated by the New Energy and Industrial Development Organization, efforts are underway to develop technologies for controlling vehicle distance and steering. This initiative aims to establish a practical automated driving and platooning system that enhances the fuel efficiency of large trucks and creates a highly efficient trunk logistics system. Within this project, cooperative adaptive cruise control (CACC) for four-vehicle platooning has been successfully demonstrated by four truck manufacturers.

CACC is a technology that improves the dynamic stability and inter-vehicle spacing of vehicle platoons by using wireless communication to share information such as velocity and acceleration among leading and neighboring vehicles. Unlike traditional Adaptive Cruise Control (ACC), CACC has been extensively researched, particularly in Europe and the United States. The California PATH program in the U.S. initiated empirical studies on CACC in the 1990s, demonstrating benefits such as enhanced fuel efficiency and increased traffic throughput due to decreased inter-vehicle distances [4]. Shladover et al. defined the fundamental structure and operational conditions of the CACC system and explored how vehicle-to-vehicle communication influences control stability [5]. From a control theory standpoint, Gaagai et al. proposed a bidirectional communication-based CACC system designed to enhance traffic safety, improve fuel economy, and increase road capacity within heterogeneous vehicle platoons [6]. Their study introduced a control strategy for maintaining optimal inter-vehicle distances with both preceding and following vehicles, theoretically analyzed the system's string stability, and validated its effectiveness through simulations.

In Japan, the Ministry of Economy, Trade and Industry (METI) and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) have initiated a national project entitled "Research, and Development and Demonstration Project for the Social Implementation of Advanced Automated Driving Systems." Since fiscal year 2017, this initiative has been conducting demonstration experiments featuring manned platooning of heavy-duty trucks equipped with CACC and lane Keep Assist (LKA), in collaboration with four major domestic truck manufacturers [7].

For the effective implementation of a practical platooning system using CACC, investigating both its functional capabilities and limitations is crucial. However, experimental evaluations using actual vehicles face constraints due to concerns about their effects on overall traffic flow, high implementation costs, and safety issues. Accordingly, simulation-based analysis is required. Because the specific control specifications of CACC systems developed by individual truck manufacturers are not publicly available, identifying and modeling each manufacturer's CACC system to conduct simulations is necessary. Although previous studies on Japanese vehicle control systems have proposed ACC models for passenger vehicles [8], published CACC models for heavy-duty trucks are currently lacking. In this study, we partnered with four major domestic truck manufacturers and conducted interviews to deduce the assumed control laws of their respective CACC systems. Utilizing actual vehicle data, we identified individual CACC models for each manufacturer. We then assessed the reproducibility of their control characteristics through simulations and proposed viable improvement methods aimed at enhancing inter-vehicle distance maintenance and responsiveness. The effectiveness of these proposed methods was validated through the simulations.

2 Vehicle Model

In the truck platooning simulation, as shown in Fig. 1, the required acceleration is determined by the CACC based on information such as the distance to and relative velocity of the front vehicle. This acceleration value is then input to the vehicle model. For the vehicle model, we used the standard model provided by TruckMaker. This model was calibrated using experimental data from actual truck platooning tests conducted at speeds ranging from 50 to 80 km/h, based on a previously developed model [9]. During the calibration process, no component-level bench testing was performed; instead, parameters were configured using publicly available data from actual test results and vehicle specifications provided by four domestic truck manufacturers.

The reproducibility of the vehicle model was assessed using two metrics: the average vehicle speed error rate $\overline{e_V}$ [%] and maximum vehicle speed error rate e_{Vmax} [%]. Both indicators fell within 15% [8]. These error rates are defined as follows:

$$\overline{e_V} = Mean_{50<V_{Measure}<8} \left(\frac{e_V}{V_{Measure}} \times 100\right), \tag{1}$$

$$e_{Vmax} = \frac{Mean_{50<V_{Measure}<80} e_V}{V_{Measure}} \times 100, \tag{2}$$

$$e_V = |V_{Simulation} - V_{Measure}|, \tag{3}$$

where $V_{Measure}$ [km/h] is the measured vehicle speed from actual driving tests, and $V_{Simulation}$ [km/h] is the vehicle speed obtained from the simulation model.

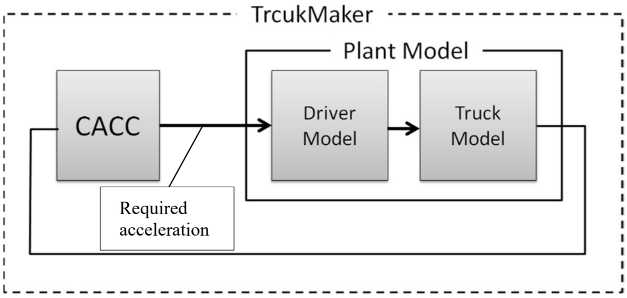

Fig. 1 Simulation configuration

3 Identifying CACC

3.1 Method of identifying CACC

From the 2019 CACC platooning test data involving actual vehicles, CACC was identified by using the required acceleration as the true value. For control purposes during the identification process, the conventional ACC lead vehicle was approximated using (4), which incorporates the CACC vehicle distance control rules [10] along with an added feedforward term. These CACC control rules have been validated as problem-free through interviews with truck manufacturing companies. The identification was performed using (5), which reflects the vehicle distance control rules [10] derived from an interview, specifically for Company C. The CACC model is identified using the equation:

$$u = A_p + K_p(L - hV) + K_d(V_p - V), \tag{4}$$

$$u = K_a(A_p - A) + K_p(L - hV) + K_d(V_p - V), \tag{5}$$

where the requested specified accelerations are represented as u [m/s^2], the distance between vehicles is L [m], the time interval between vehicles is h [s], (own) vehicle velocity is V [m/s], the lead vehicle velocity is V_p [m/s], (own) vehicle acceleration is A [m/s^2], the lead vehicle acceleration is A_p [m/s^2], and the control gains are K_a, K_p, and K_d. The same value of h = 1.6 s as used in the actual vehicle test was applied here. Identification of the driving data from the actual vehicle was achieved by distinguishing the driving and braking zones with a threshold value of −0.05 G for the required acceleration.

Specifications, including limiters and dead bands, were estimated for errors using the acceleration (A_p, A), distance error between vehicles L_e ($= L - hV$), velocity error V_e (= $V_p - V$), and requested acceleration u from the actual vehicle data of each company.

Finally, the control gain (K_a, K_p, K_d) was identified using the values based on the specifications derived from the actual vehicle measurement data in both the driving and braking zones. Equations (4) and (5) represent linear functions, with the parameters other than control gains determined from the true values by including the requested acceleration. In addition, K_a, K_p, and K_d are identified by linear least squares, while ensuring that they remain positive. Using the respective measurement data as input values, we evaluated and corrected the identification results by comparing the true value of the required acceleration with the corresponding estimated value.

3.2 Identification of the CACC of each company

The driving zones were identified using real-world vehicle data during acceleration from 50 km/h to 80 km/h at a rate of 0.05 G. The braking zones were identified using real-world vehicle data during deceleration from 80 to 50 km/h at a deceleration rate of −0.1 G.

1) Identification of the CACC of Company A

Figure 2 illustrates the actual vehicle driving data used for identifying the driving zone of Company A; this zone was determined using (4). As Fig. 2 shows, the increase in L_e is not reflected in the control input. However, we still could not confirm the existence of a limiter. Based on the assumption that no limiter exists, K_p = 0.0205 and K_d = 0.0302 were obtained as the control gains according to the identification.

Figure 4 illustrates the driving zones for both the true value of the required acceleration and the estimated value obtained through identification. As depicted, time-dependent variations exist in the rise and fall of the required acceleration; however, an overall trend can be observed. Furthermore, the mean and maximum absolute errors for the required acceleration were 0.12 and 0.51 m/s^2, respectively.

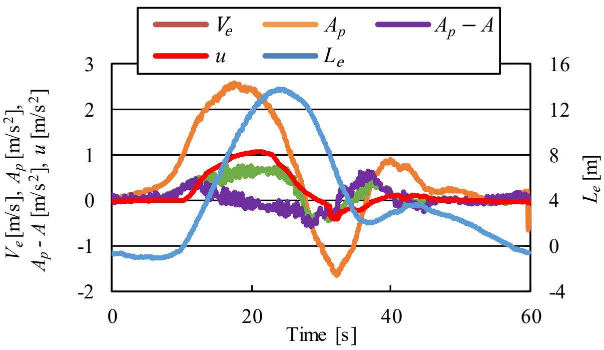

Fig. 2 Vehicle acceleration data for Company A

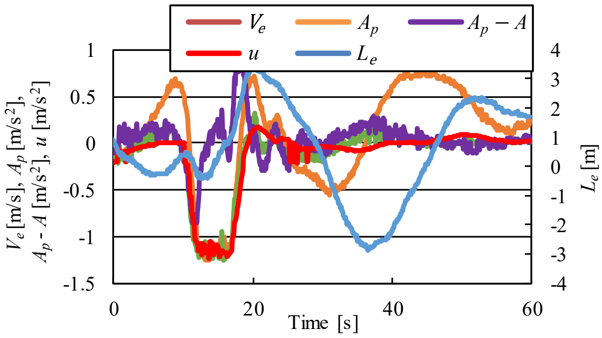

Fig. 3 Deceleration vehicle data for Company A.

Figure 5 presents the true values for the required acceleration and the estimated values derived from identification for the braking zone. This figure confirms that expressing the required acceleration is possible. The mean and maximum absolute errors for the required acceleration were 0.10 and 0.30 m/s^2, respectively.

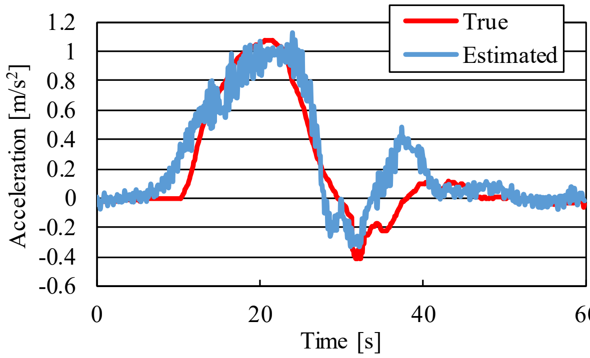

Fig. 4 Required acceleration by Company A for acceleration.

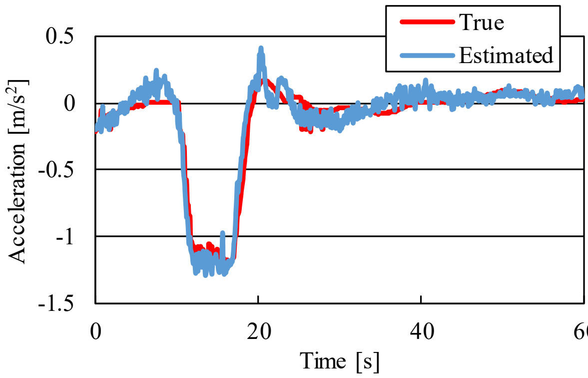

Fig. 5 Required acceleration by Company A for deceleration.

2) Identification of the CACC of Company B

Figure 6 displays the actual vehicle driving data used to identify the driving zone of Company B, determined using (4). The figure confirms that the maximum value for the required acceleration is 1 m/s^2. Consequently, the control side of the driving zone for Company B is established as

$$\begin{cases} u = u_1 \ (-0.49 < u_1 < 1), \\ \quad u = 1 \ (u_1 \geq 1). \end{cases} \tag{6}$$

The control gains were obtained as $K_p = 0.0138$ and $K_d = 0.1956$ using the identification.

Fig. 7 shows the actual vehicle data used to identify the braking zone for Company B, also identified using (4). As Fig. 7 shows, the fluctuations in L_e are not reflected in the control input. However, we still cannot confirm the existence of a limiter. Based on the assumption that no limit exists, $K_p = 0.0206$ and $K_d = 0.0072$ were obtained as the control gains according to the identification.

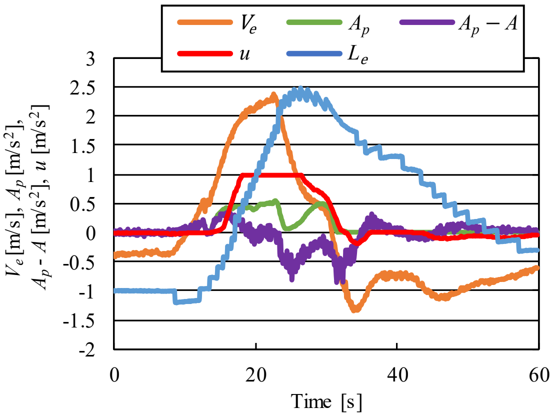

Fig. 6 Acceleration vehicle data for Company B.

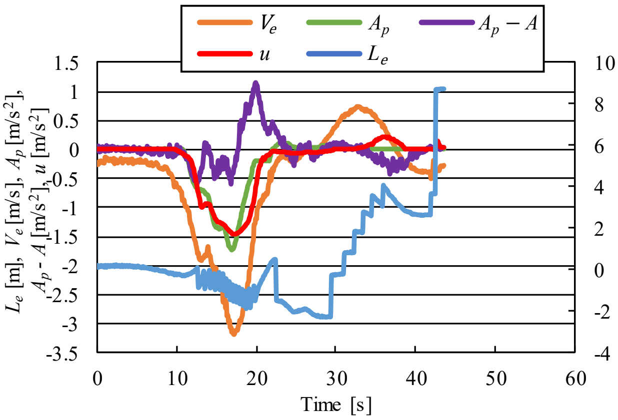

Fig. 7 Deceleration vehicle data for Company B.

Figure 8 presents the true values for the required acceleration and the estimated values obtained through identification for the driving zone. on Fig. 8. Despite the time-dependent variations in required acceleration, an overall trend was evident. The mean and maximum absolute errors for the required acceleration were 0.09 and 0.61 m/s^2, respectively.

Figure 9 depicts the true values for the required acceleration alongside the estimated values obtained through identification for the driving zone. This figure 9, also confirms the ability to represent an overall trend for the required acceleration. The mean and maximum absolute errors for the required acceleration were 0.23 and 0.51 m/s^2, respectively.

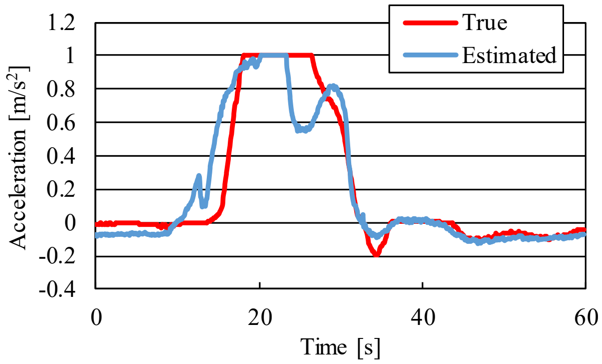

Fig. 8 Required acceleration by Company B for acceleration.

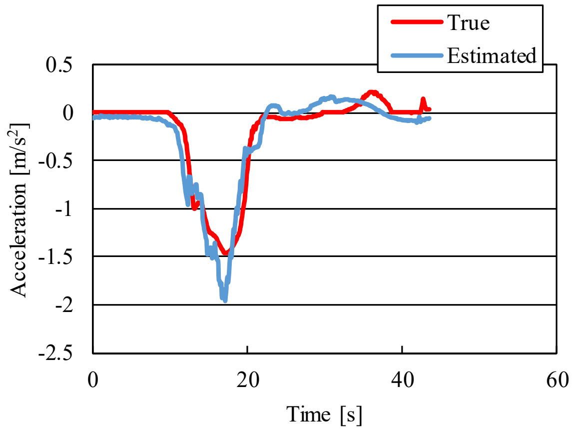

Fig. 9 Required acceleration by Company B for deceleration.

3) Identification of the CACC of Company C

Figure 10 presents the actual vehicle driving data used to identify Company C's driving zone, determined through an interview with the manufacturer and based on (5). This figure confirms that the maximum required acceleration is 0.6 m/s^2. Furthermore, it was noted that A_p was dominant at the onset of the required acceleration and was at or above 0.6 m/s^2. Consequently, the control parameters for Company C's driving zone were established:

$$\begin{cases} u = u_2 \ (-0.49 < u_2 < 0.6 \wedge u_2 > A_p), \\ \quad u = A_p \ (A_p > u_2 \wedge A_p > 0), \\ \quad u = 0.6 \ (u_2 \geq 0.6 \wedge u_2 > A_p). \end{cases} \tag{7}$$

The control gains were obtained as $K_a = 0.1191$, $K_p = 0.0141$, and $K_d = 0.3705$ using the identification.

Figure 11 shows the actual vehicle data used to identify the Company C braking zone. Based on the figure, as A_p was dominant in the braking zone, the identification in the braking zone was performed using (4). In addition, as the increase in L_e is not reflected in the control input, the specification is such that L_e is ignored if A_p is very small (within ±0.025 G in this study) or V_e is negative. When identification was conducted using these specifications, the control gains were obtained as K_p = 0.0270 and K_d = 0.0237.

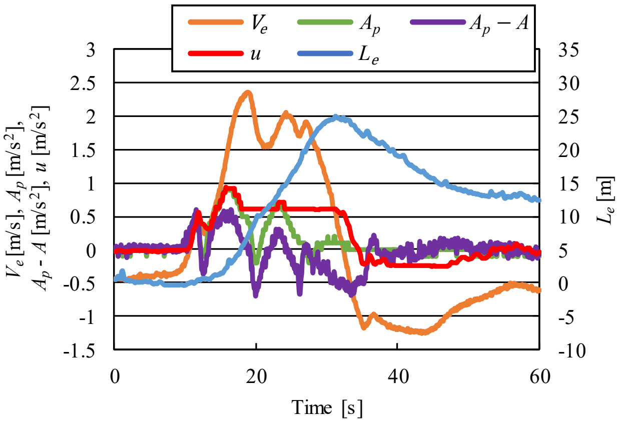

Fig. 10 Acceleration vehicle data for Company C.

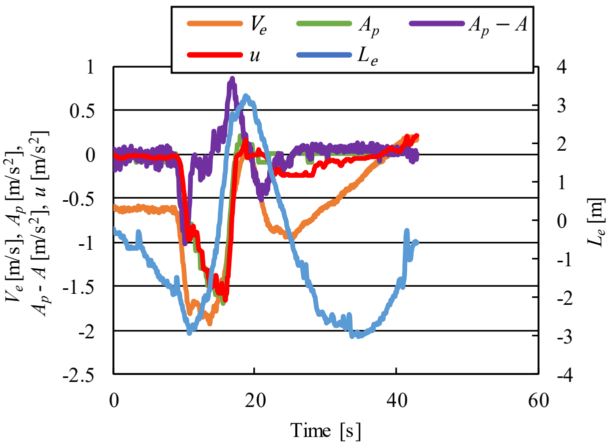

Fig. 11 Deceleration vehicle data for Company C.

Figure 12 illustrates the true values for required acceleration in comparison to estimated values obtained through identification for the driving zone. Although there is steady-state variation in the required acceleration during steady-state driving, an overall trend is discernible. The mean and maximum absolute errors for the required acceleration were found to be 0.07 and 0.32 m/s^2, respectively.

Figure 13 displays the true values of required acceleration alongside estimated values obtained through identification for the braking zone. The data demonstrates an overall trend for the required acceleration. The mean and maximum absolute errors in this case were 0.18 and 0.55 m/s^2, respectively.

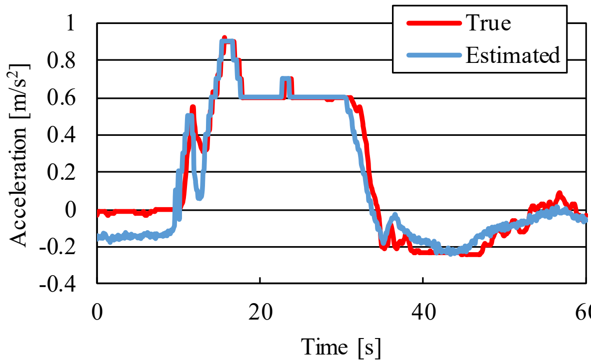

Fig. 12 Required acceleration by Company C for acceleration.

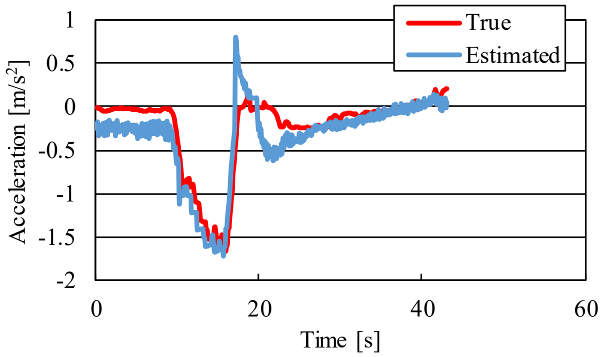

Fig. 13 Required acceleration by Company C for deceleration.

4) Identification of the CACC of Company D

Figure 14 shows the actual driving data used to identify Company D's driving zone, determined using (4). Based on this figure, because the increase in L_e is not reflected in the control input, the specification is such that L_e is ignored if A_p is very small or V_e is positive. When identification was conducted using these specifications, the control gains were obtained as K_p = 0.0133 and K_d = 0.0393.

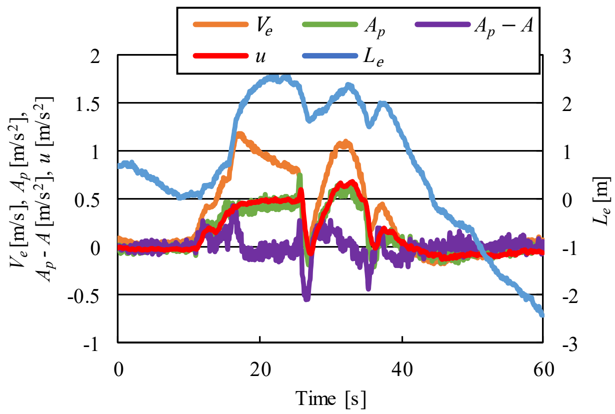

Fig. 14 Acceleration vehicle data for Company D.

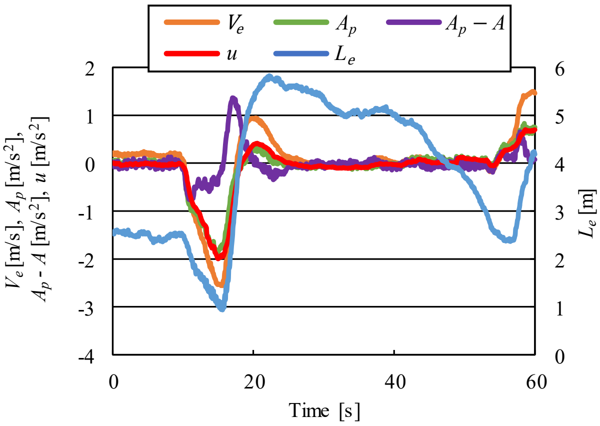

Fig. 15 Deceleration vehicle data for Company D.

Figure 16 presents the true values of required acceleration compared to estimated values obtained through identification for the driving zone. This figure confirms an overall trend for the required acceleration. The mean and maximum absolute errors were 0.05 and 0.29 m/s^2, respectively.

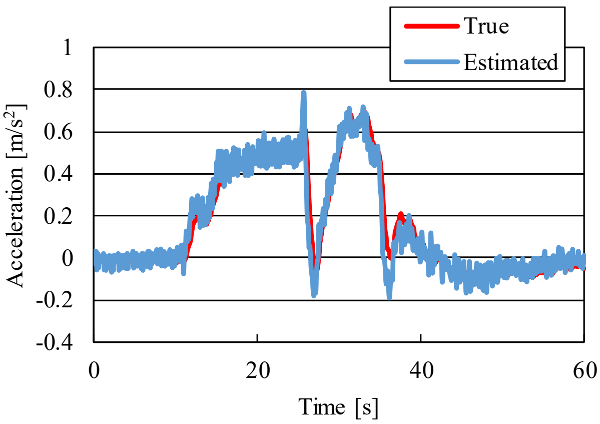

Fig. 16 Required acceleration by Company D for acceleration.

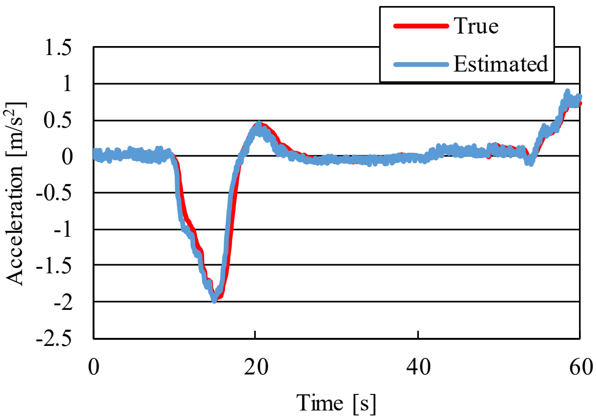

Fig. 17 Required acceleration by Company D for deceleration.

Figure 17 shows the true values along with estimated values derived from identification. This figure reaffirms the potential to depict an overall trend for required acceleration. The mean and maximum absolute errors were 0.18 and 0.52 m/s^2, respectively.

4 Reproducibility Evaluation of CACC Models

Next, we assessed the reproducibility of the real system by comparing the results from an actual vehicle test of the CACC platooning conducted in 2019, with the simulation outcomes derived from the identified CACC model.

4.1 Identification of the CACC of each company

The simulation utilized TruckMaker 8.0.1 (developed by IPG Automotive). The CACC control system was implemented for each company using Simulink R2018b (provided by MathWorks, Inc.). Simulations were conducted under the same conditions as the actual vehicle experiments to evaluate vehicle acceleration and deceleration, using vehicle speed, average speed, and maximum speed deviations as performance indices. These simulations helped in adjusting the plant model parameters for each company. Velocity identification ranged from 50 to 80 km/h, without considering disturbances. Acceleration served as the input for each plant model, whereas the required velocity was derived from the identified CACC.

Notably, during the actual vehicle test a general vehicle (leading vehicle) was set to precede the platooning vehicles, which followed the lead vehicle while it intermittently accelerated and decelerated. Therefore, identical conditions were replicated in the simulation. The order of the platoon was as follows: Companies C, D, B, and A, corresponding to the sequence in the actual vehicle experiments. The lead vehicle's velocity matched that of the actual test, accelerating from 50 to 80 km/h at 0.05 G and decelerating from 80 to 50 km/h at an acceleration of −0.1 G. The course was a straight, flat road, and all vehicles were unloaded. A communication delay of 100 ms was introduced in the acceleration of the lead vehicle A_p to reproduce the communication delay.

4.2 Simulation Results

Figures 18 and 19 illustrate the simulation results for the lead vehicle's acceleration and velocity during both the acceleration and deceleration phrases, respectively. In the actual vehicle test, the lead vehicle for Company C employed ACC. However, in the simulation, CACC was utilized, leading to differences in control strategies. Therefore, the lead vehicle was excluded from the evaluation.

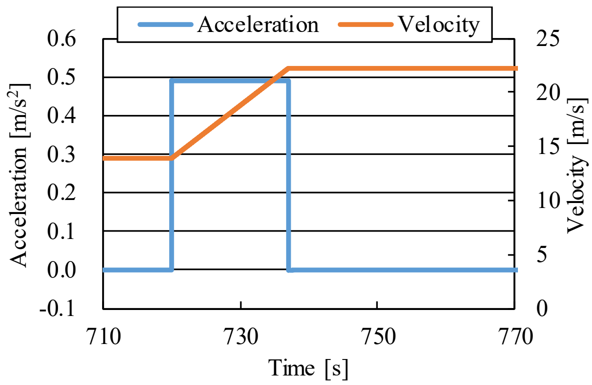

Fig. 18 Lead vehicle data of accelerated test.

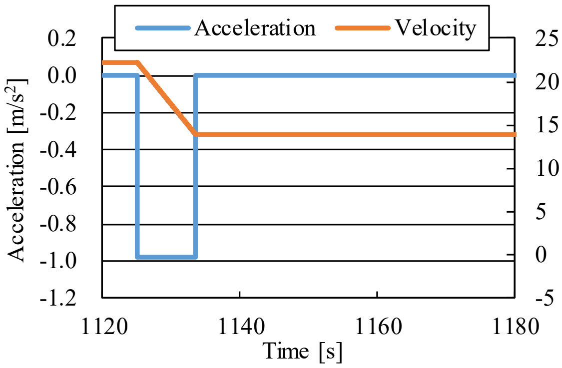

Fig. 19 Lead vehicle data of deceleration test.

Figs. 20 and 21 illustrate the changes in velocity during acceleration for the actual vehicle data and simulation results, respectively. A comparison of these figures reveals that in both the actual vehicle tests and simulations, the velocity peaked in the order of Company D, B, and A. This confirmed that the vehicle demonstrates consistent trends in velocity changes when accelerating. In addition, in the actual vehicle test data, the peak values for Companies D, B, and A were 0.6, 1.5, and 1.0 m/s lower, respectively, as compared to the simulation results. This indicates that the simulation effectively minimizes the overshoot in the driving zone.

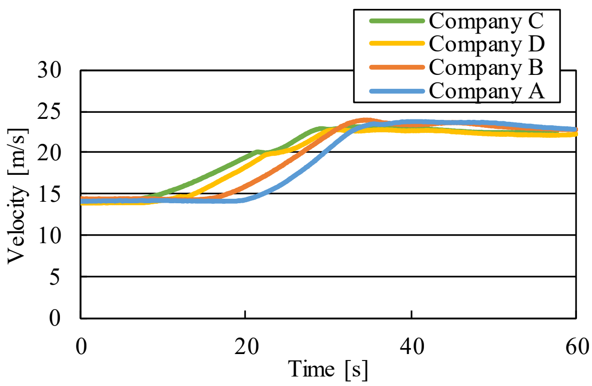

Fig. 20 Velocity response of actual vehicles for acceleration.

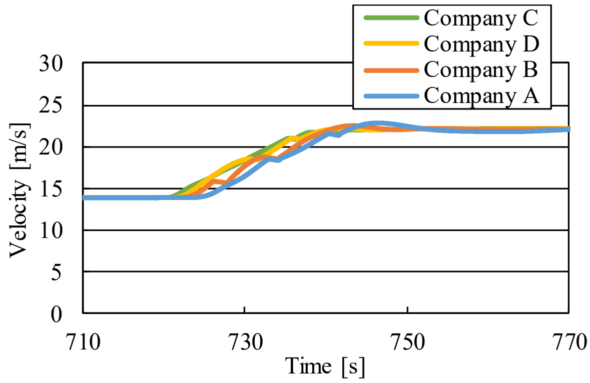

Fig. 21 Velocity response of simulation for acceleration.

Figs. 22 and 23 depict the changes in velocity during deceleration for the actual vehicle data and simulation results, respectively. Comparing these figures reveals that in both the actual vehicle tests and simulations, the velocity peaked in the order of Company D, B, and A. This further confirmed that the vehicle exhibits consistent trends in velocity changes during deceleration. Moreover, in the actual test data, the peak values for Companies D, B, and A were larger by 1.3, 0.9, and 1.2 m/s, respectively, as compared to those in the simulation. This indicates that the simulation effectively reduced the overshoot in the braking zone.

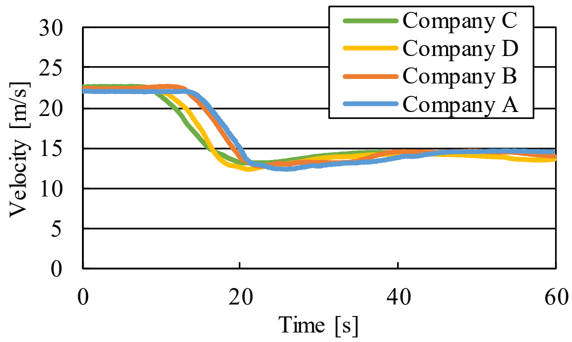

Fig. 22 Velocity response of actual vehicles for deceleration.

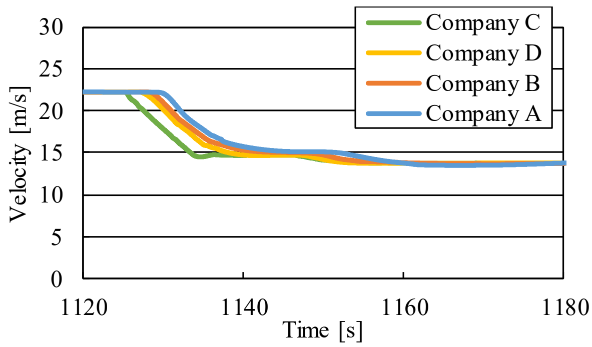

Fig. 23 Velocity response of simulation for deceleration.

5 Evaluation of Vehicle-following Performance

The simulation of multi-brand formation driving was conducted using the plant model and the CACC model identified for each company. Based on a real-vehicle experiment, a general vehicle (the leading vehicle) was positioned ahead of the vehicles in the formation, with the CACC formation adjusted to follow the accelerating and decelerating lead vehicle. In the real vehicle experiment, ACC was applied to the lead vehicle, whereas CACC was used in the simulation. Therefore, the lead vehicle in the formation was excluded from the evaluation due to the difference in control laws. The course was a straight, flat road, and all vehicles were assumed to be unloaded. A delay of 100 ms was set for the acceleration of the vehicle ahead (A_p) to reproduce the communication delay.

5.1 Simulation conditions

1) Evaluation of Vehicle-following Performance in Different Formation Orders

The effects of formation order on vehicle-following performance was assessed. For safety considerations, the performance of the vehicle immediately following the lead vehicle was evaluated during a deceleration event. In this scenario, the lead vehicle decelerated from 80 to 50 km/h at a rate of 0.1 G.

As in the controllability experiments for multi-brand platooning, eight formation sequences were simulated: B-A-C-D, B-D-C-A, C-B-A-D, C-D-B-A, A-C-D-B, A-D-C-B, D-B-A-C, and D-A-B-C. These formation orders corresponded to those used in real-vehicle experiments on multi-brand platooning. For example, the B-A-C-D sequence indicates that vehicles from Companies B, A, C, and D were arranged in that order from front to rear.

The formation with the lowest vehicle-following performance was identified based on the evaluation results.

2) Evaluation of Vehicle-following Performance Under Varying Deceleration Conditions

To investigate the performance limits of multi-brand platooning, an evaluation of inter-vehicle distance control performance was conducted using the platoon sequence with the lowest gap-keeping performance. The deceleration of the lead vehicle varied from 0.05 G to 0.5 G in increments of 0.05 G. The speed reduction scenario was from 80 km/h to 50 km/h.

3) Evaluation of Vehicle-following Performance for Changes in Time Clearance

An evaluation of gap-keeping performance was conducted by varying the target time headway h in the CACC system, using the platoon sequence identified as having the lowest gap-keeping performance. The target time headway was decreased from 1.6 s to 0.9 s in 0.1 s increments. The lead vehicle decelerated from 80 km/h to 50 km/h at a deceleration rate of 0.1 G.

5.2 Simulation results

1) Evaluation of Vehicle-following Performance in Different Formation Orders

Table 1 displays the time clearance for various platoon orders. The order that achieved the maximum average time clearance was C-D-B-A at 1.65 s, followed closely by B-A-C-D, B-D-C-A, and C-B-A-D, each at 1.64 s. The average time clearance values indicate that those closer to the target time clearance demonstrate better control performance. The highest maximum time clearance was recorded for the A-C-D-B order, measuring 2.05 s. By contrast, the minimum time clearance was smallest for the B-A-C-D conditions, at 1.29 s. Although a large maximum time clearance is not ideal for maintaining time clearance, it offers a conservative buffer relative to the target time clearance of 1.6 s. Thus, because the minimum time clearance in the B-A-C-D order was the lowest compared to its average time clearance and given that the average time clearance exceeded the target value of 1.6 s, the B-A-C-D order was chosen as having the lowest time clearance control performance.

Table 1 Time clearance control performances during 0.1 G deceleration

Platoon order	Time clearance [s]		
	Maximum	Minimum	Mean
B-A-C-D	2.01	1.29	1.64
B-D-C-A	1.93	1.51	1.64
C-B-A-D	1.99	1.34	1.64
C-D-B-A	1.85	1.40	1.65
A-C-D-B	2.05	1.35	1.62
A-D-C-B	1.94	1.36	1.58
D-B-A-C	1.94	1.43	1.60
D-A-B-C	1.94	1.41	1.59

2) Evaluation of Vehicle-following Performance Under Varying Deceleration Conditions

For the B-A-C-D platoon, selected as having the lowest time clearance control performance in the previous subsection, the evaluation of time clearance limits with respect to changes in deceleration was conducted using time clearance as the evaluation metric. Table 2 illustrates the changes in time clearance corresponding to different deceleration levels. The table confirms that the average time clearance was controlled within a range of −0.01 to +0.04 s relative to the target time clearance of 1.6 s. In addition, we observed that the minimum time clearance tends to decrease as the deceleration of the preceding vehicle increases.

Table 2 Vehicle-following performance under varying deceleration conditions

Deceleration [G]	Time clearance [s]	
	Minimum	Mean
0.05	1.14	1.61
0.10	1.29	1.64
0.15	1.19	1.62
0.20	1.07	1.61
0.25	1.02	1.60
0.30	0.96	1.59
0.35	0.92	1.59
0.40	1.02	1.60
0.45	0.97	1.60
0.50	0.93	1.59

3) Evaluation of Vehicle-following Performance for Changes in Time Clearance

For the B-A-C-D platoon, which was identified in Subsection 1) as having the lowest time clearance control performance, an evaluation of the time clearance maintenance limit with respect to changes in the target time clearance was conducted, with time clearance used as the evaluation metric. Table 3 illustrates the changes in average time clearance corresponding to variations in the target time clearance. The data confirms that the average time clearance decreases as the target time clearance is reduced, maintaining control within a range of 0 to +0.04 s relative to the target time clearance. Figure 24 displays the changes in time clearance for the lead vehicle, whereas Fig. 25 shows the changes in minimum time clearance for the three following vehicles. This figure 24 confirms that the time clearance error of the lead vehicle decreases in response to reductions in the target time clearance. Similarly, Fig. 25 shows that the following vehicles exhibit a decrease in minimum time clearance that is consistent with the lead

Table 3 Vehicle-following performance with respect to changes in target time clearance

Target time clearance [s]	Mean time clearance [s]
1.6	1.64
1.5	1.52
1.4	1.43
1.3	1.33
1.2	1.22
1.1	1.12
1.0	1.01
0.9	0.90

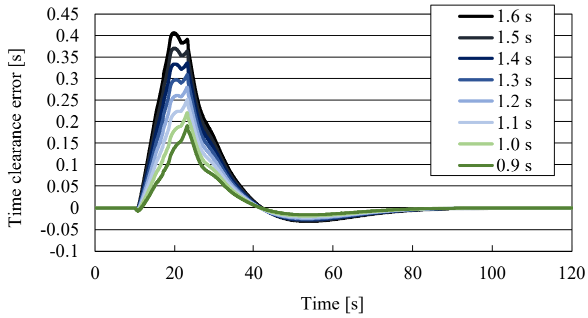

Fig. 24 Time clearance error of the lead vehicle.

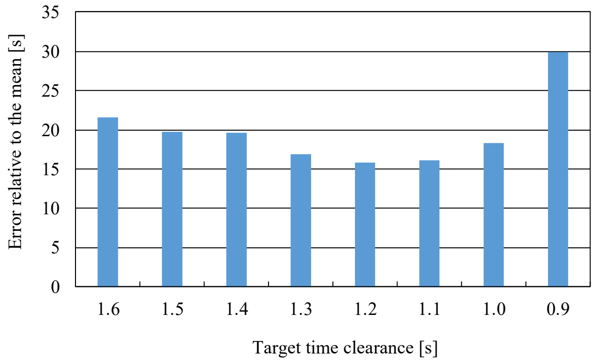

Fig. 25 Error relative to the average minimum time clearance.

vehicle's time clearance error. However, when the target time clearance is less than 1.1 s, the time clearance error increases relative to the reduction in the target time clearance.

6 Simulation on Performance Improvement of CACC

The objective of this study is to enhance the functionality of CACC for convoy driving among four major Japanese truck manufacturers. We evaluate the effectiveness of the proposed method in terms of driving stability and response through simulation using a standard vehicle model selected from the models of each company.

6.1 Identification of the CACC of each company

For the simulation of the proposed method aimed at improving CACC performance, a standard vehicle model was chosen from the vehicle models of the four truck manufacturers to ensure consistency in vehicle characteristics. Tables 4 and 5 present the step response results at accelerations of 0.05 G and −0.1 G, respectively. Interviews with truck manufacturers regarding the step response results in Tables 4 and 5 led to the selection of Company D's vehicle model as the standard specification for evaluating improvements in CACC performance.

6.2 Performance improvement based on interviews with truck manufacturers

As (4) and (5) show, conventional CACC controls the inter-vehicle distance using the acceleration of the front vehicle as A_p . This study proposes a control method that uses the desired acceleration of the front vehicle or the front leading vehicle as A_p to enhance time clearance performance within multi-brand platooning systems, particularly in light of early practical implementation. This approach helps mitigate the effects of communication delays and response lags, resulting in more stable platooning. To assess the feasibility and effectiveness of the proposed method, interviews were conducted with representatives from four major domestic truck manufacturers. These interviews confirmed that no significant compatibility or practical implementation issues with existing systems.

6.3 Simulation conditions

We compared the current specifications of CACC with the proposed improvements in normal range operations and in emergency braking scenarios. First, in the normal range, we established two conditions: acceleration from 50 to 80 km/h at a rate of 0.05 G, and deceleration from 80 to 50 km/h at a rate of −0.1 G. For emergency braking, a deceleration rate of −0.5 G was set for decelerating from 80 to 40 km/h. The vehicle model is used in all simulations. The standard model was used for all vehicles, in an empty loading condition. As described in Section 4.1, the formation configuration followed the same structure, with the CACC system following the preceding vehicle. The simulation was conducted on a straight, flat road.

6.4 Simulation conditions

1) Acceleration (0.05 G)

Table 6 presents the simulation results for an acceleration of 0.05 G and includes the average time clearance, maximum time clearance, minimum time clearance, maximum acceleration, minimum acceleration, and average jerk.

For time clearance, Table 6 indicates a general trend of decreasing time clearance across all control methods. From a comparison of the deviations from the target time clearance of 1.6 s, the evaluations ranked as follows: 1) CACC using the acceleration of the front vehicle (conventional CACC), 2) CACC utilizing the desired acceleration of the front leading vehicle, and 3) CACC employing the desired acceleration of the front vehicle. Notably, no significant difference in maximum time clearance was observed among the various control methods.

In terms of acceleration, Table 6 reveals that maximum acceleration for the CACC utilizing the desired acceleration of the front vehicle reached 0.11 G, whereas both of the reached 0.11 G, whereas both of the other control methods

methods achieved a achieved maximum acceleration of 0.12 G. The maximum acceleration in the CACC using the desired acceleration of the front vehicle was reduced to approximately 92% of that seen in the other two methods. For minimum acceleration, both the CACC using the acceleration of the front vehicle and that using the desired acceleration of the front vehicle recorded values of −0.11 G, whereas the CACC employing the desired acceleration of the front leading vehicle recorded −0.07 G. This reduction results in a minimum acceleration that is approximately 64% lower compared to the other two CACC methods.

Regarding average jerk, the data in Table 6 shows that both the CACC using the acceleration of the front vehicle and the CACC using the desired acceleration of the front vehicle recorded 0.04 m/s³. In contrast, the CACC using the desired acceleration of the front leading vehicle recorded 0.03 m/s³, indicating that the average jerk was approximately 75% lower compared to the other two CACC methods, resulting in smoother acceleration.

Table 6 Simulation results for acceleration (0.05 G)

	Front vehicle acceleration	Front vehicle regarding acceleration	Front leading vehicle regarding acceleration
Average time clearance [s]	1.52	1.38	1.41
Maximum time clearance [s]	1.60	1.60	1.60
Minimum time clearance [s]	1.30	1.13	1.18
Maximum acceleration [G]	0.12	0.11	0.12
Minimum acceleration [G]	−0.11	−0.11	−0.07
Average jerk [m/s³]	0.04	0.04	0.03

Vibrations in the transient response occur due to gear shifts during acceleration and the use of a filter that disregards time clearance errors when the acceleration of the front vehicle is within a small range (±0.025 G). Consequently, once the front vehicle's acceleration stabilizes, no feedback regarding time clearance is provided. In this study, the performance of CACC is assessed using the settling time to the steady-state value as the evaluation index. The settling time is defined as the duration required for the system to converge within ±5% of the difference between the target time clearance and steady-state value, starting from the rise time of the front leading vehicle's desired acceleration. For example, if the steady-state value is 1.7 s, the difference from the target value of 1.6 s is 0.1 s, meaning the system must converge within ±5% of 0.1 s. The rise time is identified when the second decimal place of the front leading vehicle's desired acceleration first becomes non-zero. The evaluation results are presented in Table 7. Based on the settling time of the fourth vehicle during acceleration, the performance ranking is as follows: 1) CACC using the desired acceleration of the front vehicle, 2) CACC using the desired acceleration of the front leading vehicle, and 3) CACC using the acceleration of the front vehicle. Using conventional CACC (which relies on the acceleration of the front vehicle) as a baseline, the CACC that utilizes the desired acceleration of the front vehicle converged in approximately 28% of the time, although the CACC that employs the desired acceleration of the front leading vehicle converged in approximately 46% of the time. It should be noted that during acceleration, the timing of gear shifts has a significant effect on control performance.

Table 7 Settling times for acceleration (0.05 G)

CACC type	Settling time of time clearance [s]			
	1st	2nd	3rd	4th
Using the acceleration of the front vehicle	24.32	31.23	55.01	74.35
Using the desired acceleration of the front vehicle	24.32	14.94	16.56	21.12
Using the desired acceleration of the front leading vehicle	24.32	14.95	30.06	34.23

2) Deceleration (−0.1 G)

Table 8 presents the simulation results for deceleration with an acceleration of −0.1 G, including average time clearance, maximum time clearance, minimum time clearance, maximum acceleration, minimum acceleration, and average jerk. In terms of time clearance, Table 8 reveals a trend of increasing time clearance across all control methods. Given the deviation from the target time clearance of 1.6 s, the evaluation for average and maximum time clearance ranks as follows: 1) CACC using the desired acceleration of the front vehicle, 2) CACC using the acceleration of the front vehicle (conventional CACC), and 3) CACC using the desired acceleration of the front leading vehicle. No significant differences in minimum time clearance were observed among the control methods.

In terms of acceleration, Table 8 indicates that the maximum acceleration across all control methods fell within a narrow range (±0.025 G), showing no significant performance differences. In terms of minimum acceleration, the CACC that utilized the acceleration of the front vehicle recorded −0.12 G, whereas both the CACC that employed the desired acceleration of the front vehicle and the CACC that used the desired acceleration of the front leading vehicle reported −0.15 G. Consequently, the minimum acceleration in the latter two methods was approximately 125% greater than that of the CACC using the acceleration of the front vehicle.

In terms of average jerks, Table 8 ranks the methods as follows: 1) CACC using the desired acceleration of the front leading vehicle, 2) CACC using the desired acceleration of the front vehicle, and 3) CACC using the acceleration of the front vehicle. The CACC that utilized the desired acceleration of the front leading vehicle achieved the smoothest deceleration, with an average jerk of 0.03 m/s³, which is approximately 60% lower than that of the conventional CACC using the acceleration of the front vehicle.

Table 8 Simulation results for deceleration (−0.1 G)

	Front vehicle acceleration	Front vehicle regarding acceleration	front leading vehicle regarding acceleration
Average time clearance [s]	1.84	1.82	2.60
Maximum time clearance [s]	1.96	1.94	3.21
Minimum time clearance [s]	1.60	1.60	1.60
Maximum acceleration [G]	0.006	0.003	0.003
Minimum acceleration [G]	−0.12	−0.15	−0.15
Average jerk [m/s³]	0.05	0.04	0.03

Table 9 summarizes the calculated settling times for time clearance. Evaluating the settling time of the fourth vehicle during deceleration (−0.1 G) in CACC reveals the following ranking: 1) CACC using the desired acceleration of the front vehicle, 2) CACC using the desired acceleration of the front leading vehicle, and 3) CACC using the acceleration of the front vehicle.

Under the conventional CACC method based on the acceleration of the front vehicle as a baseline, the CACC employing the desired acceleration of the front vehicle converges approximately 72% of the time, whereas the CACC using the desired acceleration of the front leading vehicle converges approximately 62% of the time.

Table 9 Settling times for deceleration (−0.1 G)

CACC type	Settling time of time clearance [s]			
	1st	2nd	3rd	4th
Using the acceleration of the front vehicle	24.32	31.23	55.01	74.35
Using the desired acceleration of the front vehicle	24.32	14.94	16.56	21.12
Using the desired acceleration of the front leading vehicle	24.32	14.95	30.06	34.23

3) Emergency braking (0.05 G)

Table 10 presents the simulation results for hard braking at −0.5 G, including average time clearance, maximum time clearance, minimum time clearance, maximum acceleration, minimum acceleration, and average jerk. The minimum time clearance across all control methods is 1.6 s, whereas the average and maximum time clearances are longer in the CACC using the desired acceleration of the front leading vehicle compared to the others. In terms of minimum acceleration, the deceleration values for the CACC using the desired acceleration of the front vehicle and that using the desired acceleration of the front leading vehicle are closer to the target deceleration than those of the conventional CACC using the acceleration of the front vehicle, indicating better responsiveness. In terms of average jerk, the CACC using the desired acceleration of the front leading vehicle achieves the lowest value, signifying the smoothest deceleration performance.

Table 10 Simulation results for emergency braking (0.05 G)

	Front vehicle acceleration	Front vehicle regarding acceleration	front leading vehicle regarding acceleration
Average time clearance [s]	1.85	1.84	2.48
Maximum time clearance [s]	2.04	2.43	3.21
Minimum time clearance [s]	1.60	1.60	1.60
Maximum acceleration [G]	0.02	0.06	0.13
Minimum acceleration [G]	−0.37	−0.41	−0.41
Average jerk [m/s^3]	0.09	0.08	0.07

The performance of CACC during deceleration is assessed using the delay time relative to the target deceleration. This delay time is defined as the interval from the initiation of the deceleration command by the leading vehicle to the moment when 50% of the maximum deceleration is achieved. The results are detailed in Table 11. In addition, Table 12 shows the minimum deceleration values for each control method during hard braking. In the CACC deceleration scenario, with a target of −0.5 G, the performance rankings are as follows: 1) CACC using the desired acceleration of the front leading vehicle, 2) CACC using the desired acceleration of the front vehicle, and 3) CACC using the acceleration of the front vehicle. Given the conventional CACC based on the acceleration of the front vehicle as the baseline, the average delay time for the entire vehicle platoon indicates that the CACC using the desired acceleration of the front vehicle reaches 50% of the minimum deceleration in approximately 75% of the time, whereas that using the desired acceleration of the front leading vehicle achieves this in approximately 67% of the time.

In terms of minimum deceleration, the order of achieved deceleration values is as follows: 1) CACC using the desired acceleration of the front leading vehicle, 2) CACC using the desired acceleration of the front vehicle, and 3) CACC using the acceleration of the front vehicle. With the target deceleration set at −0.5 G, the CACC using the acceleration of the front vehicle reaches approximately 72% of the target, that using the desired acceleration of the front vehicle achieves approximately 77%, and that using the desired acceleration of the front leading vehicle reaches approximately 82%.

Table 11 Delay times during hard braking

CACC type	Delay time [s]			
	1st	2nd	3rd	4th
Using the acceleration of the front vehicle	0.81	1.21	1.63	2.05
Using the desired acceleration of the front vehicle	0.81	1.01	1.15	1.31
Using the desired acceleration of the front leading vehicle	0.81	1.01	0.99	1.01

Table 12 Minimum deceleration values during hard braking

CACC type	Delay time [s]			
	1st	2nd	3rd	4th
Using the acceleration of the front vehicle	−0.41	−0.37	−0.34	−0.32
Using the desired acceleration of the front vehicle	−0.41	−0.41	−0.38	−0.34
Using the desired acceleration of the front leading vehicle	−0.41	−0.41	−0.40	−0.41

7 Conclusion

In this study, we analyzed CACC platooning test data from four domestic truck manufacturers to identify the specific CACC systems used by each company. The analysis showed that the identified CACC models exhibited distinct trends in the required acceleration for each manufacturer. In the driving zone, we achieved a mean absolute error of 0.1 m/s^2 for the whole platoon. However, in the braking zone, the mean absolute error was 0.15 m/s^2 for the whole platoon.

In addition, we conducted a simulation replicating the conditions of the actual CACC vehicle tests to verify the system's reproducibility. The results confirmed that trends in velocity changes were observable in both the driving and braking zones. Furthermore, the simulation demonstrated that overshoot for all vehicles could be effectively suppressed in both zones.

The effects of formation order on vehicle-following performance was confirmed using the identified plant model and the CACC model in multi-brand convoy driving. An evaluation of time clearance under a deceleration condition of 0.1 G revealed that the lowest performance occurred in the formation consisting of Companies B, A, C, and D. In this B-A-C-D formation, vehicle-following performance deteriorated as the deceleration rate increased. Moreover, when the target time clearance was varied, we confirmed that vehicle-following performance worsened as the target time clearance decreased, particularly when it dropped below 1.1 s.

8 Statements and Declarations

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