INTERNATIONAL JOURNAL OF AUTOMOTIVE SCIENCE AND TECHNOLOGY

2024, VOL. 8, NO:1, 150-158 www.ijastech.org e-ISSN: 2587-0963

Investigation of Different Communication Topologies for Cooperative Adaptive Cruise Control Systems

Beyhannur Gülden[1,2] and Mümin Tolga Emirler[1*]

[1] *Department of Control and Automation Engineering, Faculty of Electrical and Electronics, Yıldız Technical University, İstanbul, 34220, Türkiye*
[2] *eDrive & Power Electronics Departmant, FEV Türkiye, İstanbul, 34906, Türkiye*

Research Article

Abstract

After Adaptive Cruise Control (ACC) system applications, Cooperative Adaptive Cruise Control (CACC) systems are becoming an important part of automotive technology and industry in autonomous vehicles convoy applications. Together with this developing technology, CACC systems use vehicle to vehicle (V2V) communication to automatically transmit the movement information of vehicles. In this context, ACC systems use Radar or LIDAR measurements while CACC systems also consider the acceleration of the preceding vehicle. In this paper, the forms of information transmission between vehicles in autonomous vehicle convoys using CACC systems have been examined. From these forms of information transmission, the leader following, the predecessor following and the leader – predecessor following topologies have been considered. For each topology, an autonomous vehicle convoy consisting of eight vehicles was modeled in the MATLAB/Simulink environment. The feedforward and the feedback control system structure were given for CACC and ACC systems. For different communication topologies, the position-time, the speed-time, the acceleration-time and the headway time-time results were obtained. The maximum intervehicle distance error plots for each vehicle in different topology convoys were given to analyze the dynamic behavior of the convoys. The results have been analyzed in terms of the maximum intervehicle distance, the maximum speed, the minimum and the maximum acceleration, and the maximum headway time deviation from the desired headway time.

Keywords: Adaptive cruise control; Autonomous vehicle convoy; Communication topologies; Cooperative adaptive cruise control

History
Received 29.09.2023
Revised 03.12.2023
Accepted 13.01.2024

Contact
* Corresponding author
Mümin Tolga Emirler
emirler@yildiz.edu.tr
Address: Department of Control and Automation Engineering, Faculty of Electrical and Electronics, Yıldız Technical University, 34220, İstanbul, Türkiye
Tel: +902123835960

To cite this paper: Gülden, B., Emirler, M.T. Investigation of Different Communication Topologies for Cooperative Adaptive Cruise Control Systems. International Journal of Automotive Science and Technology. 2024; 8 (1): 150-158. https://doi.org/10.30939/ijastech..1368820

1. Introduction

Comfortable, reliable and fast transportation is a very important issue in people's lives. For this reason, transportation technology is one of the important factors affecting the life of a society and the environment. Due to the increasing population every day, the resulting traffic density and the increasing traffic accidents, transportation technology studies continue to produce new and effective solutions [1]. Because as the number of vehicles in the traffic increases, the traffic density also increases, which leads to accidents with fatalities, injuries or property damages. The most important factor in preventing accidents is to reduce the load of drivers in traffic. For this purpose, vehicles need to be intelligent and autonomous, they should warn the driver when necessary and provide speed control [2]. In this context, autonomous vehicle systems are being developed to protect the safety of life and ensure the comfort of drivers and passengers in traffic.

Recently, advanced driver assistance systems (ADAS) have been used in the automotive sector to help drivers by meeting these requirements and their use is becoming widespread with developing technologies [3]. These systems are designed to increase vehicle safety and enhance the driving experience. The main purpose of ADAS is to improve vehicle safety by perceiving objects, driver behavior, vehicle condition and using the existing human-machine interface [4].

Examples of systems within the scope of ADAS include systems such as automatic braking system, lane tracking system, adaptive cruise control, blind spot warning, pedestrian detection system, automatic parking assistant and rear-view camera system. Automatic braking system is a system that detects obstacles in front of the vehicle and automatically brakes. Lane tracking system is a system that detects vehicle lanes and warns the driver about going out of lane or changing lanes. Adaptive cruise control is a system that can automatically adjust the vehicle speed. It accelerates and decelerates by detecting the vehicles in front of it or the speed limits on the road. Blind spot warning is a system that warns the driver by detecting blind spots behind or on the sides of the vehicle. Pedestrian detection system is a system that can detect pedestrian movements and warn the driver. It aims to reduce the risk of collisions for pedestrians, especially in urban use. Automatic parking assistant is a system that allows the vehicle to park itself automatically. The driver indicates to the system the size and direction of the space to park, then the vehicle parks automatically. Rear view camera is a camera system that displays the area behind the vehicle. When the driver engages reverse gear, the camera image is displayed on the onboard screens, making reversing easier [5]. They constitute autonomous vehicles in the technologies under ADAS [6].

In the literature, cruise control systems are classified as traditional cruise control (CC) systems, adaptive cruise control (ACC) systems and cooperative adaptive cruise control (CACC) systems. Firstly, the system that realizes the vehicle speed value determined by the driver by controlling the accelerator pedal is called CC. CC is the basic system and primary application of other cruise control systems. In ACC systems, the purpose is to maintain the distance or headway time between the preceding vehicle and the ego vehicle [7]. The vehicle speed is controlled automatically through throttle and brake in accordance with this purpose, and its main difference from the traditional cruise control system is usually the use of a radar sensor [2]. In CACC systems, again, the purpose is to maintain the distance or headway time among vehicle, but this system is an advanced version of ACC systems. In CACC systems, in addition to radar measurement, wireless communication between the vehicles is carried out. In other words, CACC systems are systems that enable vehicles to travel in autonomous convoys in traffic by using different communication topologies between vehicles [8].

In this study, the effects of different communication topologies for a convoy of eight vehicles were examined. For this purpose, a convoy model consisting of eight vehicles was created in the MATLAB/Simulink environment and a structure was formed that allows different topologies to be obtained depending on two parameters to facilitate the transition between different topologies decently. According to the simulation results, the effect of different topologies on convoy behavior has been studied and interpreted.

The main contribution of this paper is to compare ACC predecessor following, CACC leader following, CACC predecessor following, CACC leader and predecessor following communication topologies using numerical indicators such as the maximum intervehicle distance error, the maximum intervehicle distance, the maximum speed, the minimum and maximum accelerations, and the maximum headway time deviation from the desired headway time in a simulation environment.

The outline of the rest of the paper is as follows. In Section 2, the longitudinal vehicle model used in the control system design and simulation study is described. In Section 3, the mathematical equations used for modeling the CACC system are given. In addition, forward and feedback control systems are introduced. In Section 4, the communication topologies in the literature and the topologies applied in this study are given. In Section 5, the results of the simulation study are given and analyzed. The paper is concluded with the conclusions given in Section 6.

2. Longitudinal Vehicle Model Used in Control System Design and Simulation Study

CACC systems mainly expand the capacity of ACC systems by obtaining acceleration information of the preceding vehicle via wireless communication and feeding it to the control system. The headway time in standard ACC systems can be reduced by using this additional information. In the longitudinal vehicle control systems shown in Figure 1 (ACC or CACC systems), the controller part has two control levels such as the upper-level control and the lower-level control. The upper-level control is used to calculate the desired acceleration of the vehicle. The lower-level control, on the other hand, uses different actuators such as the throttle valve and brake system to achieve the desired acceleration. For the lower-level control system design, a longitudinal vehicle model which includes driveline dynamics and engine dynamics should be employed [9, 10].

In the ideal case for upper-level controller design, the basic vehicle model can be described as follows:

$$\ddot{x}_i = u_i \tag{1}$$

where $\ddot{x}_i$ indicates the acceleration of the ith vehicle, and u_i is the control input of the ith vehicle, which can be an acceleration or a brake command depending on whether the control signal is positive or negative, respectively.

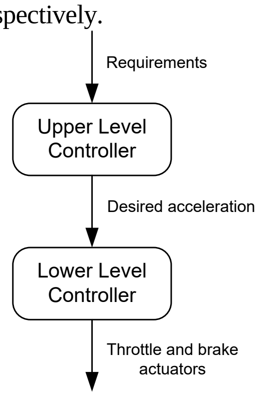

Fig. 1. General controller structure of ACC and CACC systems [9]

It is expected that the vehicle lower-level control system will imperfectly follow the desired acceleration due to the limited bandwidth of the control actuators [1]. Considering this effect of the lower-level control system in the model, only the design of the upper-level control system can be considered. In this case, by simply considering the effect of lower-level dynamics, Eq. (1) is rearranged and the longitudinal vehicle model to be used in control system design and simulation studies can be obtained as follows:

$$\tau_i \dddot{x}_i + \ddot{x}_i = u_i \quad (2)$$

where τ_i indicates the time constant of longitudinal vehicle dynamics. Using Eq. (2), the transfer function of the longitudinal dynamics of the vehicles in the convoy is written as follows [1]:

$$G_i(s) = \frac{X_i(s)}{U_i(s)} = \frac{1}{s^2(\tau_i s+1)} \quad (3)$$

The transfer function in Eq. (3) describes the longitudinal vehicle dynamics including two different dynamic parts: The first part (1/s2) is to represent acceleration to position transformation and the second part (1/(τs+1)) is to reflect basically the lower-level dynamic effects. This modelling approach is useful for simulation and control system design purposes. Also, it shows good agreement with experimental results as in [11, 12].

3. Modeling of the CACC System

3.1. Mathematical Equations of the CACC System

CACC systems use radar sensor and vehicle-to-vehicle wireless communication to maintain the desired following distance. The radar is used in the feedback section of CACC systems and provides the relative distance between the preceding vehicle and the ego vehicle. The controller, on the other hand, can control the throttle valve and, if necessary, the brake system to set the desired following distance. In addition, the acceleration of the preceding vehicle, which is used for the feedforward part of the CACC system, is transmitted to the ego vehicle using a vehicle-to-vehicle (V2V) communication. V2V communication of CACC system relies on wireless modems. These modems use the wireless access in vehicular environments (WAVE) protocol based on the IEEE 802.11p standard which utilize the licensed intelligent transportation systems (ITS) band of 5.9 GHz [13]. Figure 2 shows two CACC equipped vehicles in a convoy.

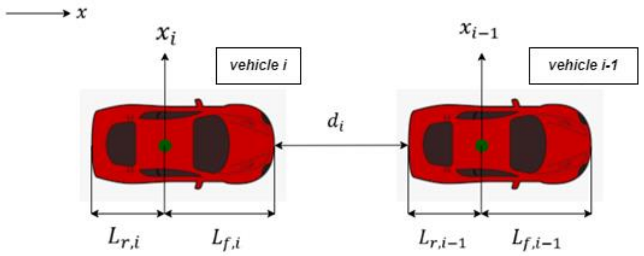

Fig. 2. Consecutive vehicles with CACC system in a convoy

In this study, the constant time headway spacing policy is used when calculating the desired following distance in the CACC system. Accordingly, the desired distance between the two consecutive vehicles can be calculated as in Eq. (4):

$$d_{r,i} = s_i + \dot{x}_i t_{hd,i} \quad (4)$$

where $d_{r,i}$ refers to the desired distance between vehicles, s_i refers to the desired safety distance between vehicles, $\dot{x}_i$ denotes the speed of the i^th vehicle, and $t_{hd,i}$ is the headway time. In the control system design part of this study, s_i is ignored and taken as zero to ease the calculations. The relative distance between two consecutive vehicles in the convoy (the distance between the rear bumper of the preceding vehicle and the front bumper of the ego vehicle) can be written as follows considering Fig. 2.

$$d_i = x_{i-1} - L_{r,i-1} - (x_i + L_{f,i}) = x_{i-1} - x_i - L_{r,i-1} - L_{f,i} \quad (5)$$

where d_i is the relative distance between the two vehicles, $L_{r,i-1}$ is the distance between the preceding vehicle's rear bumper and its center of gravity, $L_{f,i}$ is the distance between the ego vehicle's front bumper and its center of gravity. To simplify the analysis, the relative distance between vehicles (intervehicle distance) can be reduced to Eq. (6) by taking the vehicle lengths to zero:

$$d_i = x_{i-1} - x_i \quad (6)$$

ACC systems use feedback control alone to achieve the desired following distance, while the CACC system is designed as a feedback-feedforward control system. The feedforward controller is used when V2V communication is available to obtain the acceleration information of the preceding vehicle, acceleration information improves the performance of the system by allowing smaller headway times to be obtained [14]. It has a good effect on string stability and accelerates traffic flow. If an ACC system feedforward controller is used in this way, the ACC system becomes a CACC system.

The difference between the actual and the desired distance for the consecutive vehicles (intervehicle distance error) shown in Figure 2, e_i, can be expressed as in Eq. (7).

$$e_i = d_i - d_{r,i} = x_{i-1} - x_i - \dot{x}_i t_{hd,i} \quad (7)$$

3.2. Feedforward and Feedback Control System

The general block diagram of the CACC system for a single vehicle is shown in Figure 3. Here, the acceleration of the preceding vehicle is taken by the time delay β caused by the wireless communication delay between vehicles. Feedback and feedforward control systems constitute the overall CACC system as $C_{fb,i}(s)$ and $C_{ff,i}(s)$, respectively.

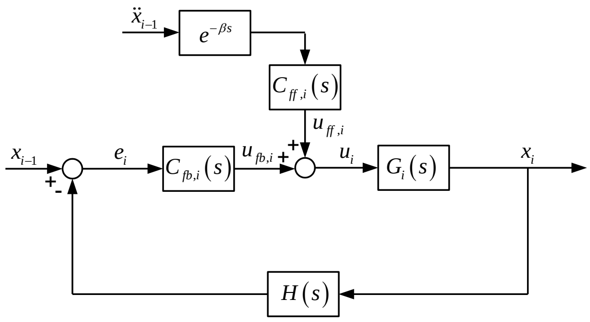

Fig. 3. CACC system structure for a single vehicle [1]

The feedback path transfer function is shown as $H_i(s)$ and is used to apply the constant time headway spacing policy:

$$H_i(s) = 1 + t_{hd,i} s \quad (8)$$

The main difference of the second part of the CACC systems from the ACC systems is the feedforward control. In CACC systems, the acceleration information of the preceding vehicle, obtained from wireless communication with some communication delay, is used in the feedforward control system to achieve a shorter headway time than possible in ACC systems. When the V2V communication connection is disabled, the feedforward part of the control block diagram in Fig. 3 disappears, and the CACC architecture turns into the ACC architecture.

The purpose of the feedforward control system is to make the error signal (e_i) zero.

According to Fig. 3, the transfer function between e_i and x_{i-1} can be written as in Eq. (9). The transfer function between e_i and x_{i-1} can be written as:

$$\frac{E_i(s)}{X_{i-1}(s)} = \frac{1-s^2C_{ff,i}(s)G_i(s)H_i(s)e^{-\beta s}}{1+C_{fb,i}(s)G_i(s)H_i(s)} \tag{9}$$

If the time delay effect $e^{-\beta s}$ on the system is not taken into account during the design phase of the control system, Eq. (9) can be written as follows, making the error signal zero:

$$1 - s^2C_{ff,i}(s)G_i(s)H_i(s) = 0 \tag{10}$$

The feedforward controller expression from Eq. (10) can be solved as follows:

$$C_{ff,i}(s) = \frac{1}{s^2G_i(s)H_i(s)} \tag{11}$$

In the simulation studies, the time delay part $e^{-\beta s}$ is added to the CACC model in order to make the simulations closer to the real application.

An alternative CACC feedforward control system design approach can be seen from [15].

The feedback control part of the ACC and CACC systems can be designed using different methods. One of the control system structures frequently used in the literature is the PD type controller [1,11,12,16]. Since the closed-loop system has free integrators on the feedforward path, the PD type controller can be used as the upper-level feedback control $C_{fb,i}(s)$of CACC systems. From the experimental implementation side, the relative position and relative velocity signals are generally read from the radar or lidar measurements and the ego vehicle's velocity and the acceleration are available from the on-board vehicle sensors. As a consequence of these measurements, the application of the PD controller is just multiplication of controller gains with the available signals.

Based on this information, the PD controller is written as in Eq. (12), where $\mathrm{k_p} = \mathrm{k_d^2} = \omega_\mathrm{k}$. Here, the design frequency for the proposed controller is shown as ω_k [11].

$$C_{fb,i}(s) = k_{p,i} + k_{d,i}s = \omega_{k,i}(\omega_{k,i} + s) \tag{12}$$

The time constant of the longitudinal vehicle model can be taken as an uncertain parameter and robust control systems can be designed as an example in [1]. Moreover, the disturbances on the convoy such as cut-in, cut-off maneuvers can be taken into consideration while evaluating the performance of the control system [17]. The effects of uncertainties and the disturbances on the convoy are not considered in this paper to focus on the effects of the communication topologies.

4. Communication Topologies

The CACC system reduces the headway time and allows autonomous vehicles to create vehicle convoys with shorter following distances. Since the distance between vehicles is reduced, the highway capacity is significantly increased, while the energy consumption is also decreased due to the reduction of aerodynamic friction and unnecessary speed changes.

Although CACC systems can be found in autonomous vehicles, the vehicle communication (information flow) topology may vary according to different methodologies. The communication topology describes the way an autonomous vehicle obtains information from other vehicles in the CACC system. Some typical types of information flow topologies can be found in the literature and flow directions are shown in Figure 4 [8,14,18].

ACC systems mainly rely on onboard sensors such as radar to detect the surrounding environment, which means that a vehicle in the system can receive information only at close range and from its predecessor. Therefore, the information flow topology that follows the predecessor vehicle is one of the typical choices for CACC systems. However, by taking advantage of vehicle-to-vehicle communication, recently proposed CACC systems allow autonomous vehicles to transfer information between each other over a much wider, and this has created different communication topologies such as the leader vehicle following, predecessor vehicle following, leader and predecessor vehicle following topologies. CACC systems provide benefits to existing transportation systems in terms of safety, mobility and sustainability. Applications of CACC systems have been proposed and developed over the years under different traffic networks. Field applications of such applications have also been made and continue to be made in order to test the effectiveness of CACC technology [8].

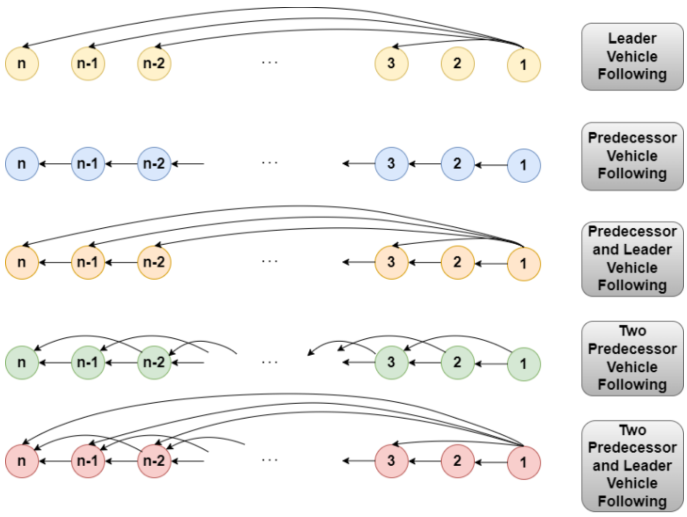

Fig. 4. Diagram of typical communication topologies [8]

In this study, leader vehicle following, predecessor vehicle following, leader and predecessor vehicle following communication topologies shown in Figure 4 were applied in the CACC system. As shown in the Figure 4, in the leader vehicle following topology, the acceleration information of the leader vehicle in the convoy is transmitted to all vehicles in the convoy. In the predecessor vehicle following topology, each vehicle in the convoy receives acceleration information from its predecessor vehicle. In the leader and predecessor vehicle following communication topology, the vehicles in the convoy receive acceleration information from both the leader vehicle and the predecessor vehicle. In the two predecessor vehicles following topology, the vehicles in the convoy receive data from the two previous vehicles. Finally, in the communication topology of following the two predecessor and leader vehicles, the vehicles in the convoy receive acceleration from two previous vehicles, leader vehicle of the convoy.

Figure 5 shows the system structure (block diagram) from which the communication topologies of ACC and various CACC systems can be obtained. A similar flexible structure proposed by Gong et al. in [18]. Also, another similar structure can be found in [19]. Accordingly, by changing the parameters a and b, different communication topologies can be obtained. The values of the parameters and the corresponding communication topologies are given in Table 1.

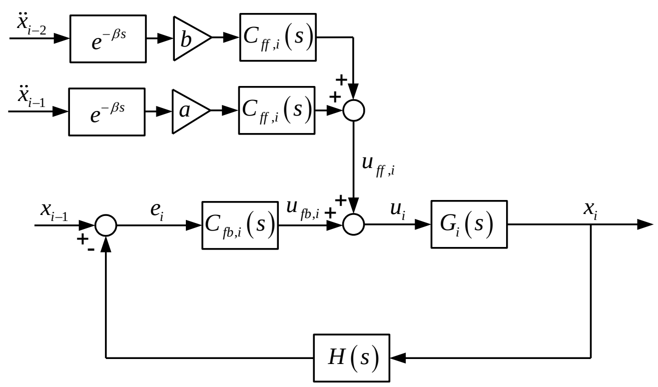

Fig. 5. System structure designed for communication topologies

Table 1. The parameter values of a and b and the related communication topologies.

Topology \ Parameters	a	b
ACC- Predecessor Following	0	0
CACC-Leader Following (LF)	0	1
CACC-Predecessor Following (PF)	1	0
CACC- Leader and Predecessor Following (LF+PF)	1	1

In simulation study, initial vehicle speeds and initial vehicle accelerations are taken as 10 m/s and 0 m/s^2, respectively. The initial position of the last vehicle is taken as 0 m, and each consecutive vehicle distance is considered as 6 m (i.e. $x_8(0)$ = 0 m, $x_7(0)$ = 6 m, …, $x_2(0)$ = 36 m, $x_1(0)$ = 42 m) This is a homogenous convoy of vehicles meaning that the vehicle models (time constant values of the vehicles) are identical and PD coefficients are the same for all vehicles. Table 2 shows the parameters used in the simulations. In the simulation scenario, the vehicles move with constant 10 m/s velocities with 6 m intervehicle distances. Then, the leader vehicle accelerates with a step acceleration of 3 m/s^2.

Table 2. The simulation study parameters.

Parameter	Value
$\boldsymbol{\tau_i}$	0.5 (s)
$\boldsymbol{t_{hd,i}}$	0.6 (s)
$\boldsymbol{\beta_i}$	0.1 (s)
$\boldsymbol{\omega_{k,i}}$	1.5 (rad/s)
$\boldsymbol{k_{p,i}}$	2.25 (1/s^2)
$\boldsymbol{k_{d,i}}$	1.5 (1/s)

Figure 6 shows the simulation results for predecessor following with ACC. From the speed-time graph in Figure 6, it can be seen that the vehicle speeds increase upstream the convoy (from the 1. vehicle to 8. the vehicle). It can be seen from the acceleration-time graph in Figure 6 that the acceleration values of the vehicles increase in positive and negative directions to achieve the desired speed towards the end of the convoy. This situation causes a shock wave in traffic and disrupts the stability of the convoy. The increase in acceleration towards the end of the convoy also affects energy efficiency and environmental pollution adversely by increasing energy consumption and emissions. The headway time reaches a maximum value of 0.7 s and oscillates around the desired headway time value of 0.6 s.

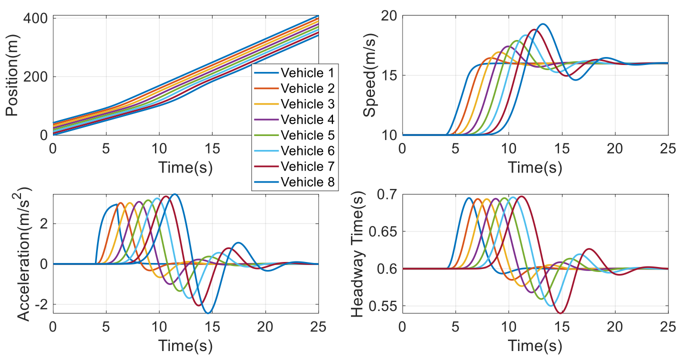

Fig. 6. ACC - Predecessor vehicle following simulation results

Figure 7 shows the simulation results of the leader vehicle following topology with CACC system. The first graph shows the distance between the vehicles. Figure 7 speed-time graph shows a different change compared to Figure 6 speed-time graph. The first difference is that the reaction time of the vehicles to speed changes has improved considerably. However, this improvement leads to a speed-pile-up around 7th second and a forced slowdown of the vehicles (to avoid a collision). The maximum speed values and maximum absolute acceleration values seen in the convoy for CACC – leader vehicle following topology are less than the convoy with ACC. Although this situation is good, even in the leader vehicle following topology, there is an increase in positive and negative acceleration values towards the end of the convoy, and string stability is not achieved. The existing problems in the system with ACC decreases, but they continue in CACC – leader vehicle following topology. The headway time values show a slight decrease compared to the ACC system as the maximum value, but continues to oscillate around the desired 0.6 s value.

In Figure 8, the predecessor vehicle following topology is applied to the CACC system. Unlike the speed-time graph in Figure 6 and Figure 7, there is no increase in vehicle speeds towards the end of the convoy. It can be seen from the acceleration-time graph in Figure 8, there is a decrease in the acceleration values required to provide the desired distance between vehicles towards the end of the convoy. The vehicles in the convoy can travel without the need for braking. String stability can be achieved in the CACC - predecessor vehicle following topology. This topology shows good results in terms of traffic flow, energy efficiency and emissions. Compared to the leader vehicle following topology, the reactions of vehicles to speed changes reduce. This situation can be seen as a disadvantage in terms of sudden acceleration and deceleration needs. The headway time deviates very slightly from the desired 0.6 s value.

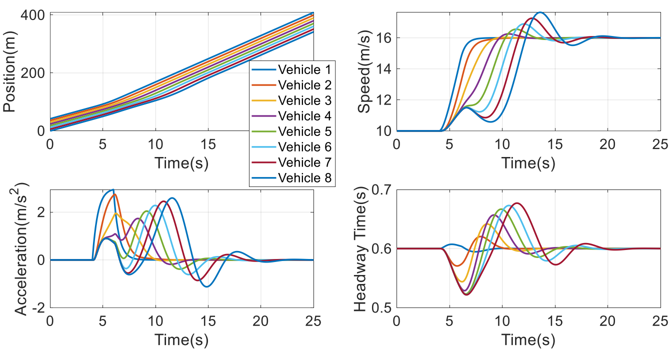

Fig. 7. CACC - Leader vehicle following simulation results

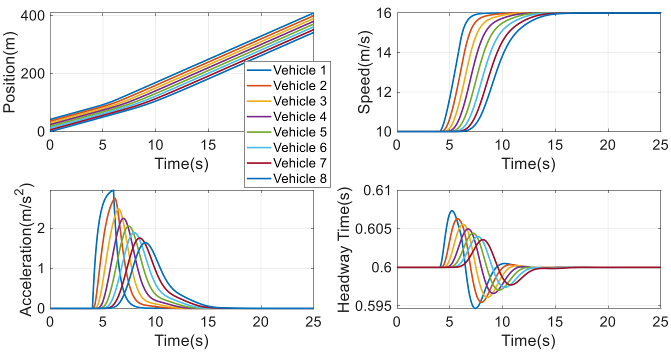

Fig. 8. CACC - Predecessor vehicle following simulation results

Figure 9 shows the simulation results of leader and predecessor vehicle following topology of the CACC system. It is seen from the speed-time graph results that the speed increases do not occur towards the end of the convoy in leader and predecessor vehicle following topology. The increases and fluctuations in vehicle accelerations towards the end of the convoy are also less than in the only leader vehicle following topology. Compared to the CACC – predecessor vehicle following topology, the vehicles react better to the speed change, but there is still a speed pile-up and forced deceleration in the convoy. String stability is not achieved, but it shows better results compared to the leader vehicle following topology. According to the results, the leader and predecessor vehicle following topology is between the leader vehicle following and the predecessor vehicle following topologies in terms of performance. It can be preferred when string stability is compromised and the reaction of vehicles to speed changes is to be increased.

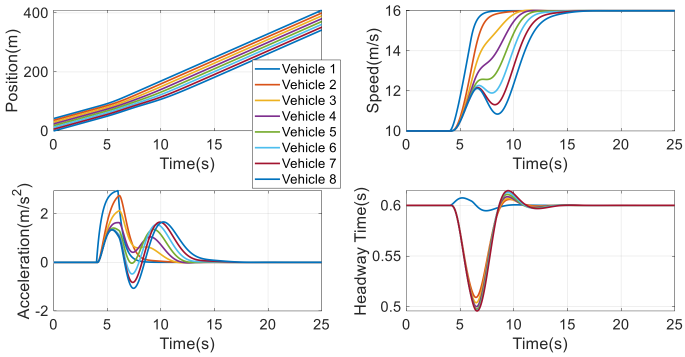

Fig. 9. CACC - Leader and predecessor vehicle following simulation results

The intervehicle distance error e_i given by Eq. (7) can be used to compare the performance of different communication topologies. The maximum intervehicle distance errors for each vehicle in ACC convoy, CACC-LF convoy, CACC-PF convoy, and CACC-LF+PF convoy are shown in Figure 10, Figure 11, Figure 12, and Figure 13, respectively.

In ACC convoy, the maximum intervehicle distance error increases towards the end of the convoy as shown in Figure 10. It reaches 1.472 m. Figure 11 shows the maximum intervehicle distance error in CACC-LF convoy. The error value increases towards end of the convoy and reaches 1.103 m. Unlike ACC convoy, the increase rate of the error value decreases upstream the CACC-LF convoy. The maximum intervehicle distance error for CACC-PF convoy is shown in Figure 11. The error value is very small compared to the other topologies. Moreover, the error values decrease towards the end of the convoy. This is very important feature to accomplish string stability. In CACC-LF+PF convoy, the error values are almost same after the vehicle 3 with the value of 1.263 m. It is a bit worse than the CACC-LF but the increase rate of the error value is almost zero. For long convoys, this will be an advantage for CACC-LF+PF topology over the CACC-LF.

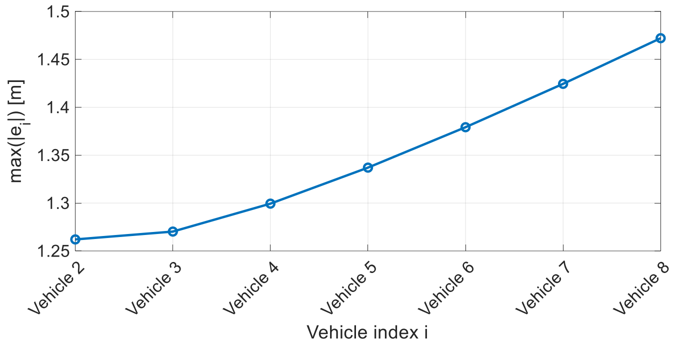

Fig. 10. Maximum intervehicle distance error for each vehicles in ACC convoy

Four different communication topologies are compared numerically in terms of maximum intervehicle distance ($\max(|d_i|)$), maximum speed ($\max(|V_i|)$), minimum acceleration ($\min(a_i)$), maximum acceleration ($\max(a_i)$), and maximum headway time deviation from the desired headway time ($\max(|t_{hd,i} - t_{hd,des}|)$) in the convoy. The desired headway time ($t_{hd,des}$) is 0.6 s in the simulations. The results are given in Table 3.

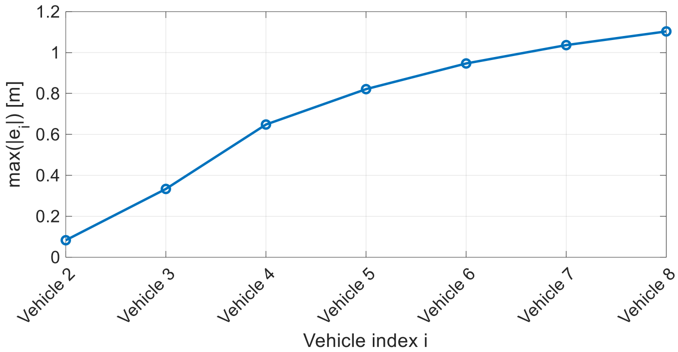

Fig. 11. Maximum intervehicle distance error for each vehicles in CACC-LF convoy

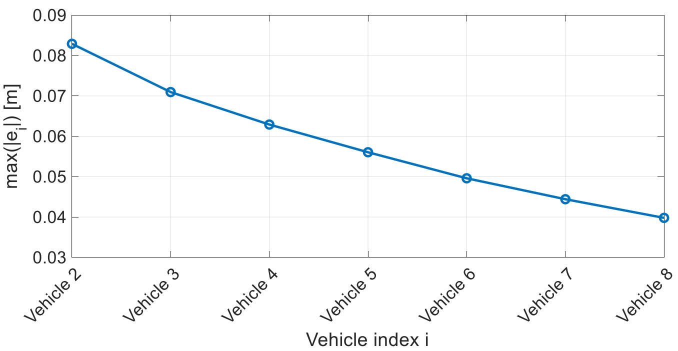

Fig. 12. Maximum intervehicle distance error for each vehicles in CACC-PF convoy

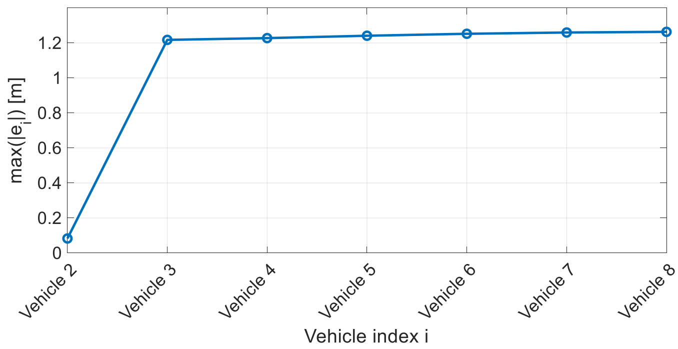

Fig. 13. Maximum intervehicle distance error for each vehicles in CACC-LF+PF convoy

According to the results in Table 3, the maximum intervehicle distance and the maximum speed in all CACC communication topologies are smaller than that of ACC as expected. The minimum intervehicle distance is obtained in CACC – PF topology. However, there is no significant difference between CACC – PF and CACC – LF+PF in terms of the maximum intervehicle distance and the maximum speed in the convoy. The maximum acceleration values in CACC communication topologies are smaller than that of ACC. These values are the same for all CACC cases because the vehicles following the leader do not exceed the leader vehicle acceleration in CACC topologies. For the minimum acceleration values, CACC – PF has the smallest value. This is an advantage of CACC – PF in terms of traffic flow, and energy issues. Also, the maximum headway time deviation from the desired headway time of CACC – PF is better than the other communication topologies.

Table 3. Numerical comparison of different communication topologies

Topology	$\max(\lvert d_i \rvert)$ [m]	$\max(\lvert V_i \rvert)$ [m/s]	$\min(a_i)$ [m/s^2]	$\max(a_i)$ [m/s^2]	$\max(\lvert t_{hd,i} - t_{hd,des} \rvert)$ [s]
ACC	12.1363	19.2904	-2.4469	3.4526	0.0970
CACC - LF	10.9589	17.6448	-1.1243	2.9451	0.0782
CACC - PF	9.0633	16.0028	-0.0026	2.9451	0.0073
CACC-LF+PF	9.6240	16.0255	-1.0677	2.9451	0.1042

6. Conclusions

In this study, the effects of different CACC communication topologies for an eight vehicle convoy were examined and compared with each other and ACC system. For this purpose, firstly, the longitudinal vehicle model used in the control system design and simulation studies was built for an eight vehicle convoy in MATLAB/Simulink environment. Then, the communication topologies utilized in this study were described. In order to facilitate the transition between different topologies, a flexible model structure has been created that allows different topologies to be obtained depending on two parameters. The different topologies have been compared by using the position-time, speed-time, acceleration-time, headway time results and the numerical indicators. According to the simulation results, the convoy can react faster to speed changes in the topologies where the leader vehicle is followed. In the predecessor vehicle following topologies, the reaction time of vehicles to speed changes may be longer than that of leader vehicle following topologies, but better results can be obtained in terms of maximum intervehicle distance and its error, maximum speed, minimum acceleration, maximum headway time deviation, string stability and traffic shock wave formation. In the future works, in order to obtain better results under disturbance and uncertainty, the robust control system design will be realized and the related design will be tested with different scenarios.

Nomenclature

$\ddot{x}_i$	: acceleration of the vehicle (m/s^2)
$\dot{x}_i$	: speed of the vehicle (m/s)
x_i	: position of the vehicle (m)
u_i	: control input
$u_{ff,i}$	: feedforward control input
$u_{fb,i}$	: feedback control input
τ_i	: time constant of longitudinal vehicle dynamics (sec)
$d_{r,i}$	: desired distance between vehicles (m)
d_i	: relative distance between vehicles (m)
s_i	: desired safety distance between vehicles (m)
$t_{hd,i}$	: headway time (sec)
$L_{r,i-1}$	: distance between the rear bumper of the vehicle and the vehicle center of gravity (m)
$L_{f,i}$	: distance between the front bumper of the vehicle and the vehicle center of gravity (m)
e_i	: feedback error signal
β_i	: communication delay
$H_i(s)$	: feedback path transfer function
$C_{ff,i}(s)$	: feedforward controller
$C_{fb,i}(s)$	: feedback controller
k_p,k_d	: PD controller coefficients
ω_k	: control design frequency (Hz)

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Beyhannur Gülden: Conceptualization, Software, Visualization, Writing-original draft, Writing-review&editing
Mümin Tolga Emirler: Conceptualization, Software, Supervision, Validation, Writing-original draft, Writing-review&editing

References

[1] Emirler M T, Güvenç L, Aksun Güvenç B. Design and Evaluation of Robust Cooperative Adaptive Cruise Control Systems in Parameter Space. International Journal of Automotive Technology 2018; 19(2): 359-367. https://doi.org/10.1007/s12239-018-0034-z

[2] Dey K C, Yan L, Wang X, Wang Y, Shen H, Chowdhury M, Yu L, Qui C, Soundararaj V. A Review of Communication, Driver Characteristics, and Controls Aspects of Cooperative Adaptive Cruise Control (CACC). IEEE Transactions of Intelligent Transportation Systems 2016; 17(2): 491−509. https://doi.org/10.1109/TITS.2015.2483063

[3] Ondoğan A. Bulanık Mantık Tabanlı Uyarlamalı Hız Kontrolü. Yüksek Lisans Tezi, Eskişehir Osmangazi Üniversitesi, Fen Bilimleri Enstitüsü, Eskişehir, Türkiye, 2022.

[4] Kabasakal B, Üçüncü M. The Design and Simulation of Adaptive Cruise Control System. Int J Automot Sci Technol. 2022; 6(3):242-256. https://doi.org/10.30939/ijastech..1038371

[5] Awad S, Colella D, Shaout A. Computer Engineering Conference. Advanced Driver Assistance Systems- Past, Present and Future. Seventh International Computer Engineering Conference (ICENCO); 2011; Cairo, Egypt. https://doi.org/10.1109/ICENCO.2011.6153935

[6] Wu C, Lin Y, Eskandarian A. Cooperative Adaptive Cruise Control With Adaptive Kalman Filter Subject to Temporary Communication Loss. IEEE Access 2019; 7: 93558-93568. https://doi.org/10.1109/ACCESS.2019.2928004

[7] Trudgen M, Mohammadpour J. Robust Cooperative Adaptive Cruise Control Design for Connected Vehicles. Proc. ASME Dynamic Systems and Control Conference; 2015; Columbus, Ohio, USA. https://doi.org/10.1115/DSCC2015-9807

[8] Wang Z, Wu G, Barth M J. A Review on Cooperative Adaptive Cruise Control (CACC) Systems: Architectures, Controls, and Applications. 21st IEEE International Conference on Intelligent Transportation Systems (ITSC); 2018; Maui, HI. https://doi.org/10.1109/ITSC.2018.8569947

[9] Rajamani R. Vehicle Dynamics and Control. Springer Newyork (2nd Edition), 2011.

[10] Pardhi S, Deskmukh A, Ajrouche H. Modelling and Simulation of Detailed Vehicle Dynamics for the Development of Innovative Powertrains. Int J Automot Sci Technol. 2021; 5(3):244-253. https://doi.org/10.30939/ijastech.931066

[11] Naus G J L, Vugts R P A, Ploeg J, van de Molengraft M R J G, and Steinbuch M, String-Stable CACC Design and Experimental Validation: A Frequency-Domain Approach. IEEE Transactions on Vehicular Technology 2010; 59(9):4268–4279. https://doi.org/10.1109/TVT.2010.2076320

[12] Güvenç L, Uygan İ M C., Kahraman K, Karaahmetoğlu R, Altay İ, Şentürk M, Emirler M T, Hartavi Karci A E, Aksun Güvenç B, Altuğ E, Turan M C, Taş Ö S, Bozkurt E, Özgüner Ü, Redmill K, Kurt A, Efendioğlu B. Cooperative Adaptive Cruise Control Implementation of Team Mekar at the Grand Cooperative Driving

Challenge. IEEE Transactions on Intelligent Transportation Systems. 2012; 13(3): 1062 –1074. https://doi.org/10.1109/TITS.2012.2204053

[13] Güvenç L, Aksun Güvenç B, Emirler M T. Connected and Autonomous Vehicles. Internet of Things and Data Analytics Handbook: Chapter 35, Book Editor: Hwaiyu Geng, Wiley, 2016. https://doi.org/10.1002/9781119173601.ch35

[14] Darbha S, Konduri S, Pagilla P R. Benefits of V2V Communication for Autonomous and Connected Vehicles. IEEE Transactions on Intelligent Transportation Systems, 2018; 20(5): 1954-1963. https://doi.org/10.1109/TITS.2018.2859765

[15] Villamil A, Gonzalez A, Franchi N, Fettweis G. Feedforward Filter Design for CACC with N-Vehicle Look Ahead: A Frequency Domain Approach for Further Optimization of Radio Resource Usage. In: 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall); 2020; Victoria, Canada. https://doi.org/10.1109/VTC2020-Fall49728.2020.9348642

[16] Ma F, Wang J, Yang Y, Zhu S, Gelbal S Y, Aksun Güvenç B, Güvenç L. Stability Design for the Homogeneous Platoon with Communication Time Delay. Automotive Innovation 2020; 3(2): 101-110. https://doi.org/10.1007/s42154-020-00102-4

[17] Sarıhan S, Yalçın M F, Kaynar E, Emirler M T. Otonom Araçlar için Kooperatif Seyir Kontrol Sistemi Tasarımı ve CARLA-MATLAB/Simulink Ortamında Benzetimi. TOK 2023 Otomatik Kontrol Türk Milli Komitesi Ulusal Kongresi; 2023; İstanbul Technical University, İstanbul.

[18] Gong S, Zhou A, Peeta S. Cooperative Adaptive Cruise Control for a Platoon of Connected and Autonomous Vehicles Considering Dynamic Information Flow Topology. Transportation Research Record 2019; 2673(10), 185–198. https://doi.org/10.1016/j.trpro.2019.05.014

[19] Flores C, Spring J, Nelson D, Iliev S, Lu X-Y. Enabling Cooperative Adaptive Cruise Control on Strings of Vehicles with Heterogeneous Dynamics and Powertrains. Vehicle System Dynamics, 2023; 61(1): 128-149. https://doi.org/10.1080/00423114.2022.2042568