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Evaluating Efficiency of Connected and Autonomous Vehicles with Different Communication Topologies

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Abstract: Connected and autonomous vehicles (CAV) employ vehicle-to-vehicle communications to safely drive in a platoon with short inter-vehicle distances, which can improve traffic throughput and reduce fuel consumption. With the development of wireless communication technology, more and more information can be used for vehicle controllers. However, is more information better? In this paper, a fuel economy-based performance evaluation index is established for evaluating the efficiency of CAVs driving in a platoon with different communication topologies. Four typical communication topologies that describe the CAV with different amounts of information are studied by the linear controller. The differential evolution algorithm is used to solve the parameters. Due to the increase in information, more control parameters need to be computed, and it is hard to find an optimal solution. So, the simulation results show that CAV with more information did not obtain a better fuel economy.

Keywords: connected and autonomous vehicle; communication topologies; vehicle platoon

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1. Introduction

Car travel provides convenience to people's lives but also has a certain negative impact on the environment and the community, namely, huge fuel consumption and traffic safety. Despite decades of research by many scientists from different areas, these problems are still not completely solved. With the development of information technology, especially the advent of fifth-generation (5G) for vehicular communications, these problems are trying to be solved from a novel perspective of communication, computation, and control [1,2]. Some special roads, notably the intersection [3] and ramp [4], should expect a vehicular communication network.

At the intersection, traffic signals always let the vehicles slow down and accelerate away. A significant amount of fuel is spent, and rear-end accidents often happen in this process. Through vehicle-to-infrastructure (V2I) communications, information about traffic lights and the states of vehicles is easy to obtain, and many control methods have been proposed to solve these problems. By controlling vehicles, an optimal velocity planning scheme based on probabilistic prediction of traffic signal timing is used to increase vehicles' energy efficiency [5]. On the other hand, through the control of traffic signals, under consideration of vehicle fuel consumption and dynamic characteristics, a dynamic traffic signal timing optimization strategy was proposed to reduce vehicle travel delays around intersections and enable traffic safety [6].

As a frequently encountered traffic scenario, on-ramp merging has also been studied under the conditions of vehicle-to-vehicle (V2V) and V2I communication. For two strings of vehicles at highway on-ramps, a rule-based cooperative merging strategy was proposed to optimize the merging sequence and improve traffic efficiency and safety [7]. Time delay is never an avoidable topic for communication. In the scenario of on-ramp merging for CAVs, the statistical characteristics of the communication delay are explored from the literature and the real field test, and a communication delay estimation model based on statistical techniques is proposed to compute the corresponding optimal control law [8].

Vehicle platoons are another important practical application for vehicular communications. With high traffic density, high speed, low wind resistance, and so on, the platoon has attracted a lot of attention. In the early PATH program [9], control architecture, control scheme, sensor and actuator, communication networks, stability analysis, and any other topics were studied [10]. At the beginning of the 21st century, theoretical analysis was carried out with a linear model; local quadratic performance indexes and linear quadratic optimization were used to obtain the decentralized overlapping longitudinal control for each individual vehicle [11]. Experiments with real cars have been conducted to demonstrate the feasibility and potential of the vehicle platoon at the National Institute of Advanced Industrial Science and Technology in Japan [12].

Since then, vehicle platoons have drawn a lot of attention in the fields of Intelligent Transportation Systems (ITS). According to research findings, the following vehicle using only relative spacing information to follow a constant distance behind the preceding vehicle leads to string instability. It is found that a small disturbance acting on one vehicle can propagate and have a large effect on another vehicle [13]. To overcome the instability of the platoon, wireless communication is used by vehicles to exchange information. Cooperative adaptive cruise control, as an extension of adaptive cruise control, has an improvement in traffic flow stability and a slight increase in traffic flow efficiency [14]. In fact, wireless communication is inevitable with limited communication bandwidth and time-varying transmission delays. Some improved cooperative adaptive cruise control systems have been developed, for example, the event-triggered control scheme and communication strategy for platoons [15]. In addition, only a few following vehicles can access the information of the leader, which is also normal for vehicle communication networks. A distributed adaptive event-triggered observer and the car following control protocol are proposed for vehicular platoon control [16].

With the rapid deployment of vehicle-to-everything (V2X) techniques, CAVs can receive more information from others, with the condition that different numbers of vehicles' position, velocity, acceleration, etc. But how much information should be sufficient for a vehicle platoon? Almost all of us have been conditioned to think that the more, the better. But is this really the case? In this paper, a vehicle platoon with different communication topologies has been studied, and each CAV can receive information from a different number of other CAVs through the V2V and V2X. Every CAV's driving decision is computed by the received information. The remainder of this paper is organized as follows. In Section 2, the system structure of the CAV platoon with four typical communication topologies is presented. The fuel economy-based performance evaluation index and its optimization-solving method are presented in Section 3. The simulation results of the platoon with specific scenarios are presented in Section 4, along with some conclusions and discussion in Section 5.

2. Problem Formulation

Consider a platoon of $N + 1$ CAVs running on a straight, flat road, with the leading CAV indexed by 0 and N following CAVs indexed from 1 to N. All following CAVs can receive information from neighboring CAVs and make a control decision to maintain a similar velocity with the leading CAV.

2.1. Communication Topologies

Laser, radar, camera, GPS, and light detection and ranging are the usual sensing components for the CAV. The sensing components enable the CAV to know the surrounding environment, especially the obstacles. Other CAV's information such as position, velocity, and acceleration, can be received through wireless communication. If the CAV wants any other CAVs' information, it can be received with the help of a communication network. In this paper, referring to the research in [17], four typical communication topologies have been considered.

Firstly, the predecessor-following (PF) communication topology is shown in Figure 1. In the PF communication topology, each CAV can only receive information from its preceding CAV. The lead CAV was driving with a higher level of control, and it did not receive any information from the following CAV.

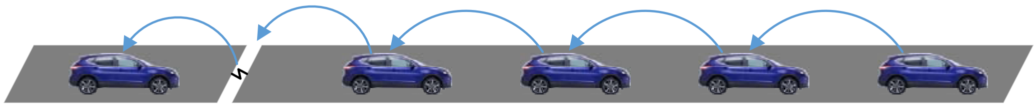

Figure 1. Predecessor following communication topology.

Secondly, the predecessor leader following (PLF) communication topology is shown in Figure 2. Compared with the PF communication topology, the second-following CAV and its following CAVs in the PLF can receive additional information from the leading CAV.

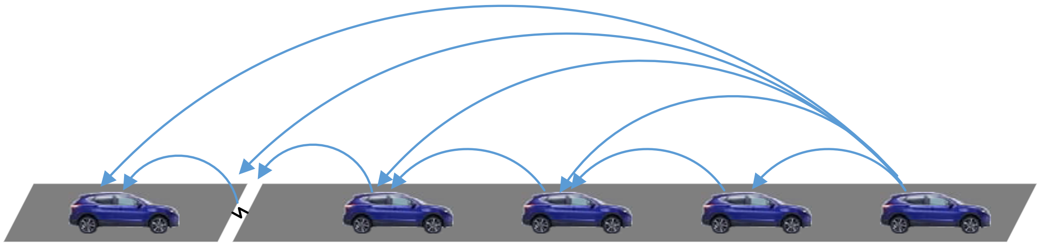

Figure 2. Predecessor leader following communication topology.

Thirdly, the two predecessor-following (TPF) communication topology is shown in Figure 3. Compared with the PF communication topology, the second following CAV and its following CAVs in the TPF can receive one more CAV's information from the second in front of themselves.

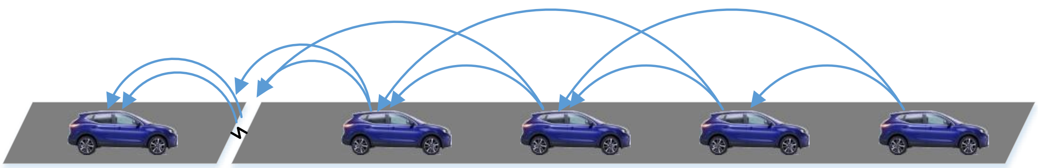

Figure 3. Two predecessors follow a communication topology.

Lastly, consider the PLF and TPF communication topologies; the fourth communication topology, named a two predecessor leader following (TPLF), is shown in Figure 4. Each following CAV under the TPLF communication topology can receive at most the other three CAVs' information.

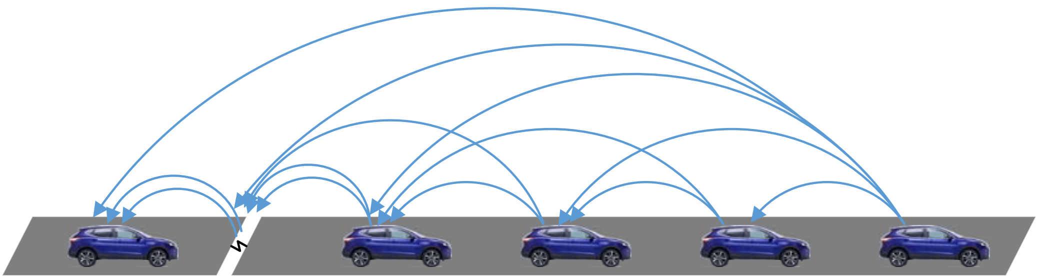

Figure 4. Two predecessor leaders following communication topology.

The CAVs in these four communication topologies can receive different amounts of information. It assumes that all communication connections are one-way, which means that the preceding CAVs do not need to receive information from their followers.

2.2. Individual CAV Dynamics

Consideration of the platoon of CAVs with identical dynamics, and their dynamics can be described with nonlinear differential equations as shown in [18–20]. And a simplified vehicle dynamics model is often adopted for platoons, which is obtained through the feedback linearization of the nonlinear differential equations, and the longitudinal dynamics of the *i*th CAV in the platoon, as follows:

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = a_i(t) \\ \tau \dot{a}_i(t) + a_i(t) = u_i(t-\phi) \end{cases} \quad (1)$$

where $u_i(t)$ represents the control input of the *i*th CAV; $x_i(t)$, $v_i(t)$ and $a_i(t)$ denote the position, velocity, and acceleration of the *i*th CAV at instant t, respectively; τ and ϕ characterizes the inertial time lag of the powertrain system.

2.3. Distributed Controllers for CAVs

With the help of wireless access in vehicular environments (WAVE), dedicated short-range communication (DSRC), and other communication technologies, the CAVs can receive more information from other CAVs. How to use this information is a difficult problem. In this paper, refer to [21–23]. All CAVs with the same distance, velocity, and acceleration are the best state for a platoon, so the linear controller is adopted, which is easy to implement for CAVs. When CAVs are under the PF communication topology, the distribution controller for *i*th CAV can be designed as

$$u_i(t) = k_x[x_{i-1}(t) - x_i(t) - D - t_h \cdot v_i(t)] + k_v[v_{i-1}(t) - v_i(t)] + k_a[a_{i-1}(t) - a_i(t)] \quad (2)$$

where D is the standstill distance, $x_{i-1}(t)$ denotes the position of $i-1$th CAV that is driving in front of the *i*th CAV; t_h is a pre-specified time headway between any two consecutive vehicles in the platoon; k_x, k_v and k_a are controller parameters. In this mode, only three parameters need to be calculated.

Consider the CAVs with PLF communication topology; the form of controller for the first following CAV is the same as in Equation (2). The controller for the second following CAV and its followers can be designed as

$$\begin{aligned} u_i(t) = {} & k_x^i[x_{i-1}(t) - x_i(t) - D - t_h \cdot v_i(t)] + k_v^i[v_{i-1}(t) - v_i(t)] + k_a^i[a_{i-1}(t) - a_i(t)] \\ & + k_x^{i0}[x_0(t) - x_i(t) - i \cdot (D + t_h \cdot v_i(t))] + k_v^{i0}[v_0(t) - v_i(t)] + k_a^{i0}[a_0(t) - a_i(t)], \end{aligned} \quad i > 1 \quad (3)$$

where $x_0(t)$, $v_0(t)$ and $a_0(t)$ denote the position, velocity, and acceleration of the leading CAV. Each following CAV's controller has six parameters, which are named by letter k. The subscript and superscript for letter k is used to distinguish the controller parameters. For example, the subscript v is related to the parameter of velocity. Consider a platoon of N CAVs, there are $(N-2) \times 6 + 3$ parameters need to be calculated.

Under the condition of TPF communication topology, the form of controller for the first following CAV is the same as Equation (2), and the other following CAVs' controller can be designed as

$$\begin{aligned} u_i(t) = {} & k_x^i[x_{i-1}(t) - x_i(t) - D - t_h \cdot v_i(t)] + k_v^i[v_{i-1}(t) - v_i(t)] + k_a^i[a_{i-1}(t) - a_i(t)] \\ & + k_x^{i,i-2}[x_{i-2}(t) - x_i(t) - 2 \cdot (D + t_h \cdot v_i(t))] + k_v^{i,i-2}[v_{i-2}(t) - v_i(t)] \\ & + k_a^{i,i-2}[a_{i-2}(t) - a_i(t)], \end{aligned} \quad i > 1 \quad (4)$$

Similarly, consider a platoon of N CAVs, there are $(N-2) \times 6 + 3$ parameters need to be calculated under the condition of TPF communication topology.

At last, considering the TPLF communication topology, the first following CAV only receives the leading CAV's information, so the form of the controller is the same as Equation (2), and there are three parameters that need to be calculated. The second following CAV in this mode can receive the leading and its preceding CAVs' information, so the form of the controller is the same as Equation (3), and there are six parameters that need to be calculated. The third following CAV and its followers' controller can be designed as

$$\begin{aligned} u_i(t) \quad &= k_x^i[x_{i-1}(t) - x_i(t) - D - t_h \cdot v_i(t)] + k_v^i[v_{i-1}(t) - v_i(t)] + k_a^i[a_{i-1}(t) - a_i(t)] \\ &+k_x^{i0}[x_0(t) - x_i(t) - i \cdot (D + t_h \cdot v_i(t))] + k_v^{i0}[v_0(t) - v_i(t)] + k_a^{i0}[a_0(t) - a_i(t)] \\ &+k_x^{i,i-2}[x_{i-2}(t) - x_i(t) - 2 \cdot (D + t_h \cdot v_i(t))] + k_v^{i,i-2}[v_{i-2}(t) - v_i(t)] \\ &+k_a^{i,i-2}[a_{i-2}(t) - a_i(t)], \end{aligned} \quad i > 2 \tag{5}$$

From the third following CAV and its followers, there are nine parameters for each CAV, and there are $(N-3) \times 9 + 6 + 3$ parameters need to be calculated for a platoon under the TPLF communication topology.

According to Equations (2)–(5), even if the simple linear controller for CAVs is used, as more information is gathered through the communication network, more parameters need to be calculated. In the platoon with PF communication topology, the controller parameters can be resolved by many methods, such as linear quadratic regulator (LQR). Even with the LQR control scheme, the optimal parameters are still difficult to find because the weighting matrix used for optimization is not unique. The platoon's PLF, TPF, and TPLF communication topology, with the increase of the number of parameters, makes the optimal analytical solution more difficult to derive, particularly since the platoon's objective cannot be described as a simple error.

3. Performance Evaluation Measures

String stability is an important requirement for the platoon, which is defined as the attenuation of disturbances [13]. But why do the CAVs need to drive in a platoon. That is because of the lower fuel consumption, higher traffic efficiency, and increased safety. So, in this section, an evaluation methodology with consideration of fuel consumption, traffic efficiency, and safety is designed.

3.1. Evaluation Indicators

For the CAVs' fuel consumption, too many factors contribute to it, such as engine speed, gear ratio, torque, temperature, and so on. In all these factors, vehicle acceleration and velocity are the main contributors. Following the idea of [24,25], the following fuel consumption model is adopted, which has been studied in [26].

$$F(a,v) = \max\left\{ \left(\alpha + \beta_1 \cdot v \cdot R_T + \left[\beta_2 \cdot M \cdot a^2 \cdot v \right]_{a>0} \right),\ \alpha \right\} \tag{6}$$

where α is the constant idling fuel rate, M is the vehicle mass, β_1 is an efficiency parameter that relates fuel consumption to the energy provided by the engine and β_2 relates fuel consumption to positive acceleration. R_T is the total tractive force required to drive the vehicle, which is the sum of the rolling resistance, air drag force, cornering resistance, inertia force, and grade force defined as

$$R_T = b_1 + b_2 \cdot v^2 + M \cdot a + g \cdot M \cdot G \tag{7}$$

where b_1 is the drag force due to rolling resistance and b_2 represents the drag force due to aerodynamic resistance. G is the road gradient (negative downhill) and g is the gravitational acceleration.

For traffic efficiency, the CAVs need to drive the longest distance in the shortest time, and this target is easy to model. For traffic safety, the gap between CAVs in that platoon is greater, so rear-end collision accidents happen with a small possibility. But the long gap against traffic efficiency, to keep things simple, has been described in a qualitative way. The general performance evaluation index is expressed as follows:

$$J = \begin{cases} \sum_{i=1}^{N-1} (F_i/D_i) & for\ \ x_{i-1}(t) - x_i(t) > L_V \\ \infty & for\ \ x_{i-1}(t) - x_i(t) \leq L_V \end{cases} \tag{8}$$

where L_V is length of the CAV, F_i denotes the ith CAV's fuel consumption in total, D_i is the distance traveled by the ith CAV in the platoon. The performance evaluation index in the above equation is also an optimization objective for the controllers. To ensure that each vehicle's control input and speed are within a given admissible range, the following constraints have been imposed:

$$\begin{cases} v_{\min} \leq v_i(t) \leq v_{\max} \\ a_{\min} \leq a_i(t) \leq a_{\max} \end{cases} \tag{9}$$

where $a_{\min}$, $a_{\max}$ are the minimum deceleration and maximum acceleration for each CAV, and $v_{\min}$, $v_{\max}$ are the minimum and maximum speed limits, respectively. According to Equation (8), the platoon with a longer travel distance and less fuel consumption that objective functional has a smaller value. But if the gap between any two lead-follow CAVs is less than the vehicle length, which means the rear-end collision accident has happened, then it can set the objective function with a value of infinity; it can also be called one vote against, meaning veto.

3.2. Solving Method

In Algorithm 1, at each instant, the algorithm first updates every CAV's state based on vehicle dynamics and constraints. Then it will check whether there are two succession CAVs that have crashed or not. If it has happened, the algorithm will be killed and restarted with other parameters produced by DEA. In this way, it will find a group of parameters for Equations (2)–(5) for which Equation (8) obtains an optimal value, which means that the platoon will drive a long distance with less fuel consumption.

According to the evaluation indicators introduced above, the solution of Equation (8) under the constraints of Equation (9) is a nonlinear optimization problem, and it is difficult to find an analytic solution for the parameters in Equations (2)–(5). So the differential evolution algorithm (DEA, refer to [27]) as an efficient method for optimizing real-valued multimodal objective functions is adopted in this paper. The computational process for DEA is easily found on the internet, so we will not go into the details of DEA. In order to reduce computational burden, the computed fitness function for DEA has been defined as

Algorithm 1. Calculate the fitness function.

Inputs: All parameters named letter k in Equations (2)–(5) produced by DEA, Vehicle physical parameters.
1: **while** $t_k < t_{end}$ **do**
2: **for** $i = 1, 2, \ldots\ldots, N$ **do**
3: update $x_i(t_k)$, $v_i(t_k)$, $a_i(t_k)$ based on $v_i(t_{k-1})$, $a_i(t_{k-1})$, $\dot{a}_i(t_{k-1})$ within the constraints of (9)
4: **if** $x_{i-1}(t_k) - x_i(t_k) \leq L_V$, **break** and return maximum number allowed by the computer
5: **else continue** and calculate the fuel consumption based on Equations (6) and (7)
6: **end if**
7: **end for**
8: **for** $i = 1, 2, \ldots\ldots, N$ **do**
9: calculate $u_i(t_k)$
10: calculate $\dot{a}_i(t_k)$
11: **end for**
12: **end while**
Output: Sum of each CAV's total fuel consumption divided by its travelled distance

4. Numerical Results

In this section, a series of numerical experiments have been conducted to show the efficiency of CAV with different communication topologies. The position, velocity, acceleration, and fuel consumption of CAV are computed using the parameters given in Table 1.

Table 1. Setting of parameters in the simulation.

Coefficient	Value	Unit	Coefficient	Value	Unit
α	0.444	mL/s	ϕ	0.1	s
M	1200	kg	L_V	5	m
β_1	0.09	mL/kj	D	7	m
β_2	0.03	$\text{mL}/(\text{kJ}\cdot\text{m/s}^2)$	$v_{\min}$	0	m/s
b_1	0.333	kN	$v_{\max}$	30	m/s
b_2	0.0008	$\text{kN}/(\text{m/s})^2$	$a_{\min}$	−4	m/s^2
τ	0.2	s^{-1}	$a_{\max}$	3	m/s^2

The DEA used in this paper is based on Python 3.9 with SciPy 1.7.1, which is open source software for mathematics, science, and engineering. The fitness function for DEA is defined in Section 3. In order to reduce the searching space for the parameters that have been defined in Equations (2)–(5) with the letter k, set the bounds as $k_*^* \in [0, \quad 5]$, and which means that the parameters solved by DEA will be greater than 0 but less than 5. The maximum number of generations is set to 1000, and the pop size is set to 30. Other parameters for DEA are set as defaults. The program runs on a regular laptop (Operating System: Windows 10, CPU: Intel i5-7200U, RAM: 12GB).

In the simulations, the initial states of all CAVs are set as $x_i(0) = (N-i)\cdot 10$, $v_i(0) = 0$, $a_i(0) = 0$. Consider a simulation scenario with 60 s in which the control input of the leading CAV is given by

$$u_0(t) = \begin{cases} a_{\max}, & 0s < t \le 10s \\ -a_{\max}, & (10s < t \le 50s) \wedge (4s < t\%10 \le 5s) \\ a_{\max}, & (10s < t \le 50s) \wedge (5s < t\%10 \le 6s) \\ 0, & otherwise \\ a_{\min}, & 50s < t \le 60s \end{cases} \tag{10}$$

According to the above equation, the leading CAV is driving with a special velocity profile, as shown in Figure 5. Evaluating the CAVs in a platoon by setting the leading CAV with a time-varying velocity can test the control scheme under different communication topologies as far as possible.

By using Algorithm 1, it can obtain the controller parameter for the platoon under the PF communication topology.

$$[k_x, \quad k_v, \quad k_a] = [0.62639021,\ 1.73182882,\ 0.92274993] \tag{11}$$

In the same way, the controller parameter for PLF, TPF, and TPLF communication topologies can be obtained, but the other three controllers' numerical values are not shown in this paper. But some special phenomena from the following figures can be found in this paper.

In the comparison of experimental results shown in Figures 6–9, a huge difference cannot be found between the PF, PLF, TPF, and TPLF, especially the platoon under PF, TPF, and TPLF communication topologies with similar velocity evolution curves. The platoon with PLF communication topology, the first following CAV, tracked the leader slowly in the beginning because the optimized objective function considered total fuel consumption and traffic efficiency but not the tracking error.

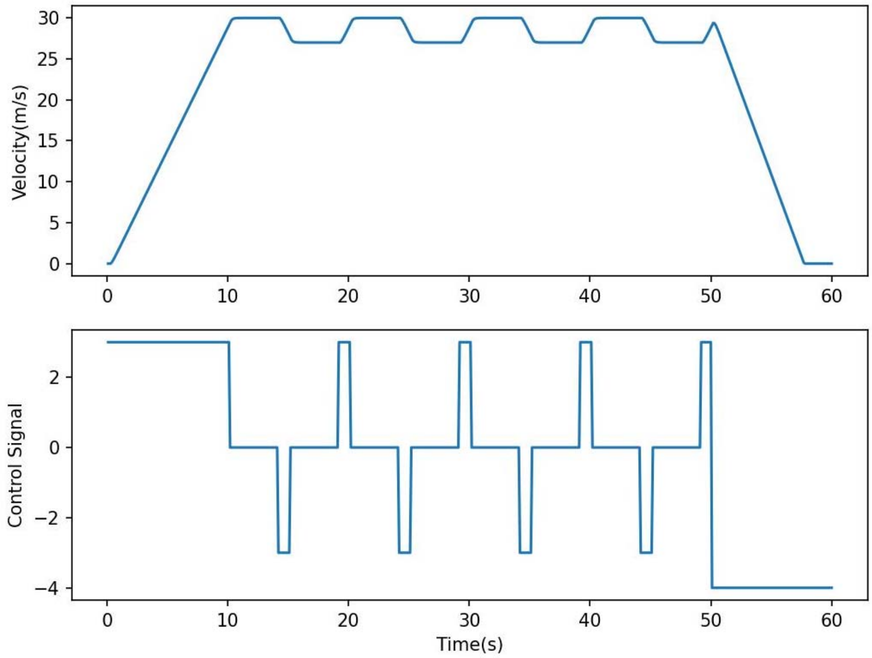

Figure 5. The velocity and control signal for leading CAV.

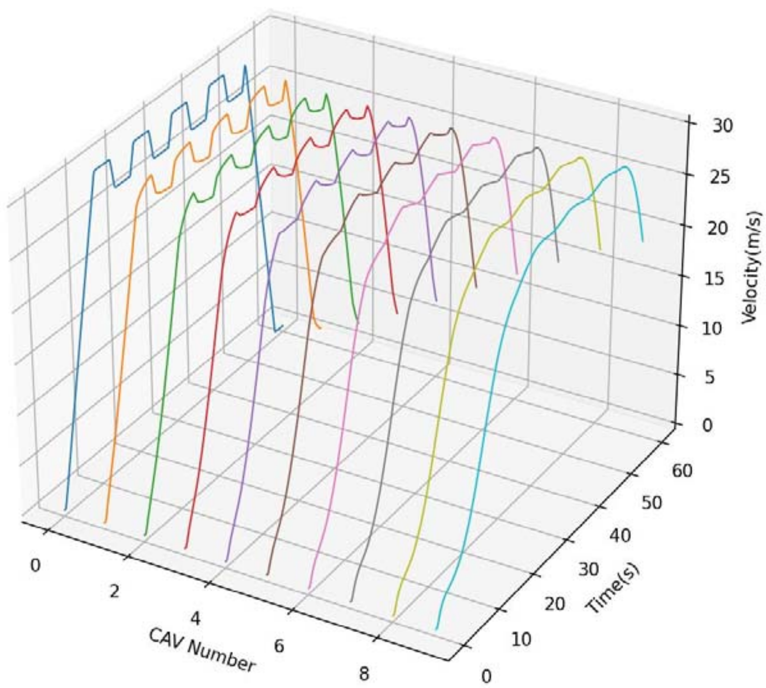

Figure 6. Simulated time response of the velocity for a platoon under PF communication topology.

Each CAV's fuel consumption is divided by its distance travelled with the result shown in Figure 10. It can be found that the platoon under the PLF communication topology has better fuel economy than others. The platoon under the PF communication topology has the worst fuel economy among these four modes. The TPLF communication topology is slightly better than the TPF communication topology in terms of fuel economy. It cannot be found that the platoon with TPLF communication topology, where CAVs can receive more information than others, is the best way.

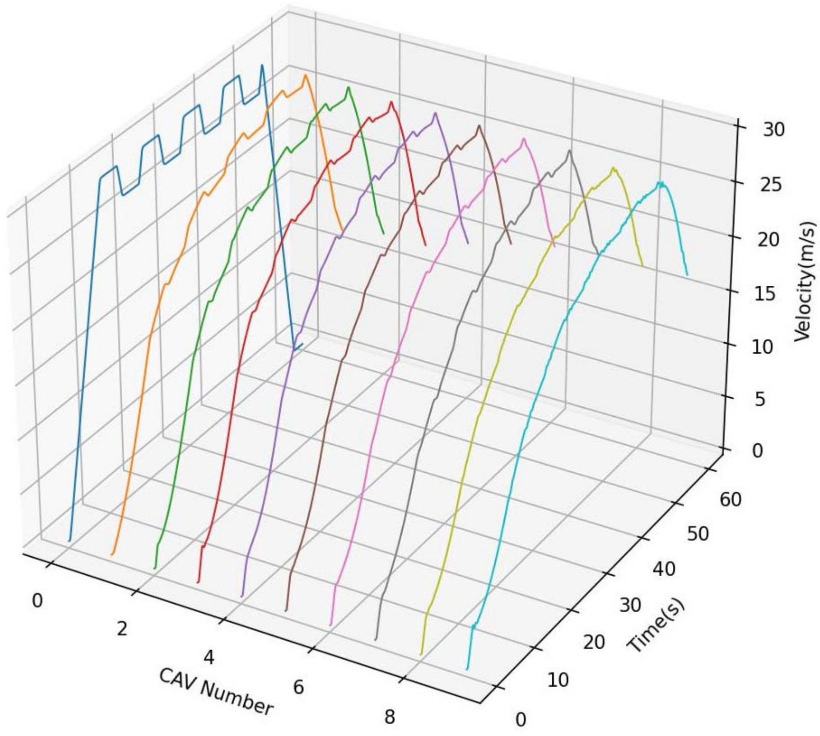

Figure 7. Simulated time response of the velocity for a platoon under PLF communication topology.

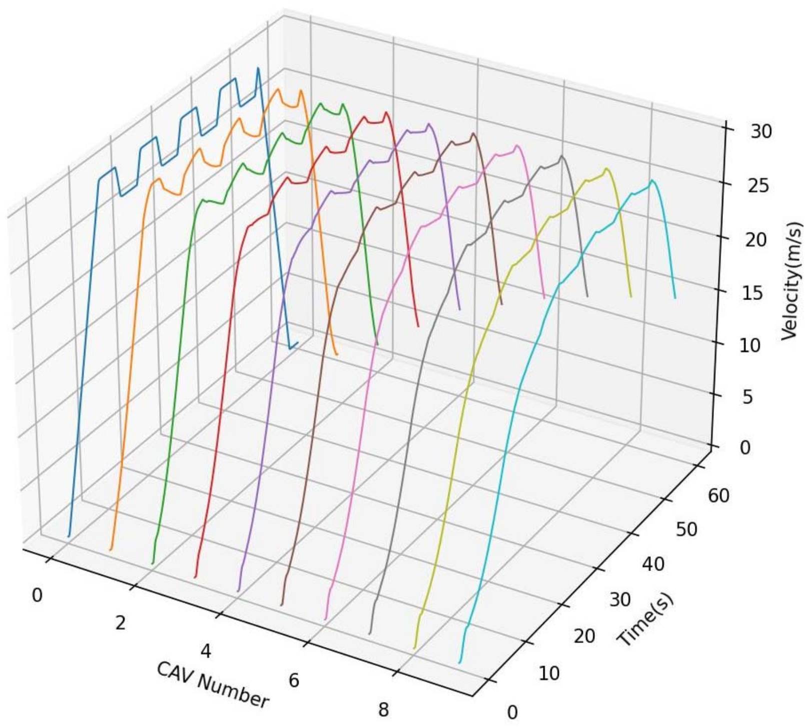

Figure 8. Simulated time response of the velocity for a platoon under TPF communication topology.

It can also be observed that the CAVs far from the leading CAV have better fuel economy than those driving close to the leader in any communication topology. This may be caused by the disturbance produced by the leading CAV with the preload command, and the platoon is string stable, attenuating the disturbance along the platoon [13]. The CAV (i.e., leading CAV) that creates the disturbance, in which all following CAVs under the PLF and TPLF communication topologies can receive information from them directly, might explain why the PLF and TPLF communication topologies have better fuel economy than others. The CAVs under the TPLF communication topology with more controller parameters need to be computed than PLF, and it has made it difficult for the DEA to find an optimal solution even with massive calculations. More than 2,163,474 groups of parameter combinations have been tested by the DEA in this paper, but it still has not found a better solution than the CAVs with the PLF communication topology, and this is just a simple linear control scheme.

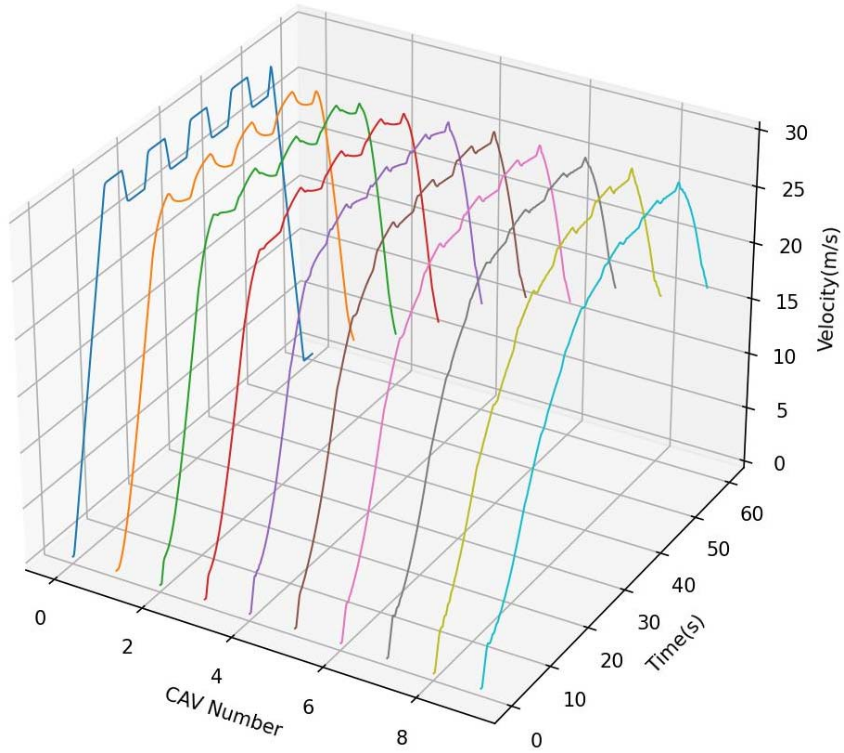

Figure 9. Simulated time response of the velocity for a platoon under TPLF communication topology.

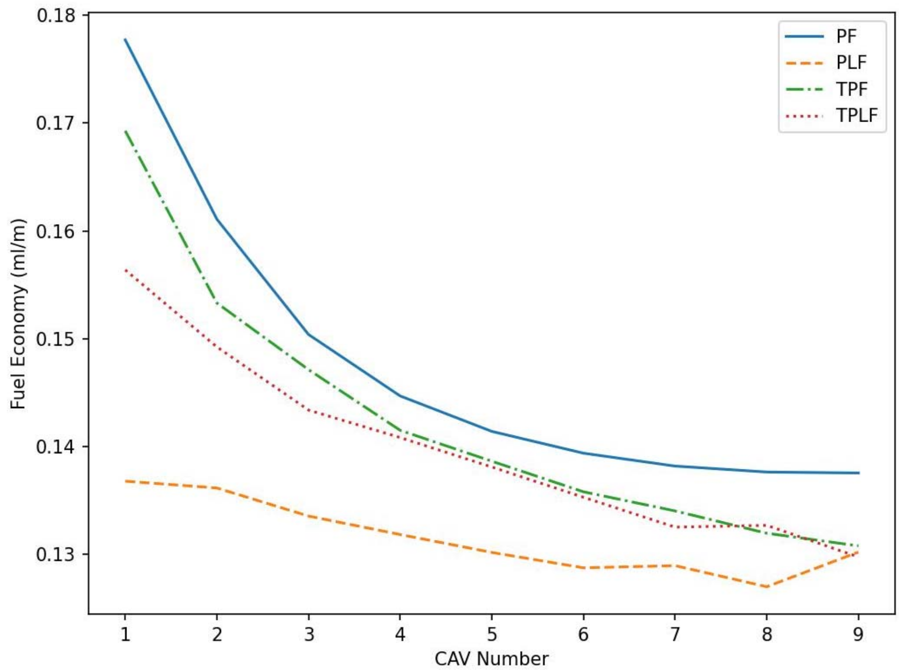

Figure 10. The fuel economy for each CAV.

5. Conclusions and Discussion

In this paper, the CAVs driving in a platoon with different communication topologies have been discussed. Four typical communication topologies, referred to simply as PF, PLF, TPF, and TPLF, are studied with a linear control scheme. In different communication topologies, CAVs would receive different numbers of other CAVs' information. The performance evaluation index is established by considering fuel economy. Four controllers' parameters are computed by DEA with the constraints of vehicle dynamic, velocity limit, et al. A specific scenario is designed for evaluating the efficiency of CAVs with different communication topologies. A simulation experiment found that the PLF communication topology has better fuel economy than others; however, it is not the TPLF communication topology that receives more information than others. There are several reasons accounting for this phenomenon.

(1) The solution computed by DEA is just not accurate. Due to the large number of controller parameters and the nonlinear objective function, it is not possible to obtain an analytical solution for these linear controllers, so the DEA is adopted in this paper. The DEA is a simple and efficient global optimization algorithm for complex nonlinear programming problems. At the same time, the DEA is one kind of heuristic algorithm, and it cannot go through all cases. So, the solution is not necessarily the best, and it could be a locally optimal solution. This difficult problem is not merely for the linear controller; other control schemes also cannot obtain the analytical solution by increasing the information;

(2) The simulation scenario or optimized objective function was designed inappropriately. Although there is only one simulation scenario and one optimized objective function shown in this paper, the optimized objective function with consideration of tracking error, fuel consumption, and traffic efficiency, as well as some other scenarios, has been tested by the authors. It cannot be found that more information is helpful for CAVs driving in a platoon with those linear controllers;

(3) Event-triggered control schemes may be suitable for CAVs with complete information. The simulation results show that the PLF communication topology obtained the best performance index among them, followed by the TPLF communication topology. Both of them share one trait: all following CAVs can receive the leading CAV's information, which is affected by preloaded commands. So, the CAV driving in a platoon should consider the velocity difference and gap between itself and its predecessor. In most cases, and in some special cases, other CAVs could be awakened by an event trigger, which can also reduce the communication burden.

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