Control Aspects of Cooperative Adaptive Cruise Control in the Perspective of the Cyber-physical System

Ankur Jain, B.K. Roy

Abstract--- Cooperative adaptive cruise control (CACC) enables vehicles to communicate with each other to form a group which coordinate for advanced applications on highways and freeways. There are three backbone technologies, autonomous cruise control, collision avoidance and dedicated short-range communication (DSRC), to realise it. In this paper, we aim to control longitudinal motion of homogeneous vehicle platoon. We proposed a model following control strategy to control and manage real-time dynamics of a platoon in the perspective of the cyber-physical point of view. We have assumed wireless transmission for information flow and considered a constant delay in message hopping. Numerical simulation is done to show the feasibility of this technique. Cooperative adaptive cruise control (CACC) enables vehicles to communicate with each other to form a group which coordinate for advanced applications on highways and freeways. There are three backbone technologies, autonomous cruise control, collision avoidance and dedicated short-range communication (DSRC), to realise it. In this paper, we aim to control longitudinal motion of homogeneous vehicle platoon. We proposed a model following control strategy to control and manage real-time dynamics of a platoon in the perspective of the cyber-physical point of view. We have assumed wireless transmission for information flow and considered a constant delay in message hopping. Numerical simulation is done to show the feasibility of this technique.

Keywords: Cyber-physical system, Vehicle platoon, Cooperative adaptive cruise control, Model following control.

INTRODUCTION

Growing population demanding smart logistics solutions to delivers goods with minimum delay. Increasing traf- fic demand is the significant cause of congestion in major urban areas and corridors. Intelligent surface transportation system plays a vital role in minimisation of delay by pro- viding reliable transportation of domestic passenger traffic and goods movement for domestic and international trade[1]. Even though the transportation plays a precise role in the economic development of any country but it is also impacting negatively on as poor traffic flow. In recent year, numerous concerns have raised to increase traffic flow capacity along with passenger safety by the governments of various nations, technological institutions and academic research[2], [3], [4]. Roads have limited capacity, by only effectively utilisation we can significantly increase this capacity. To solve this problem, various researchers come up with cooperative adaptive cruise control system[5]. In this systems, grouping vehicles into platoons can improve road capacity and energy efficiency. With the advance of inter-vehicle and short-range communication technologies[6], the performance of platoons can be further enhanced by V2V, V2I or vehicular ad-hoc network (VANET)[7], [8]. CACC system is allowing smaller headway which results in high road throughput. Platoon dynamics evolve in real time which is monitored and controlled by a distributed / centralised controller/s which are tightly-coupled with the wireless network. So that, we can see CACC in the perspective of the cyber-physical system[1], [2], [3].The architecture of the vehicle platoon as shown in Fig. 1.

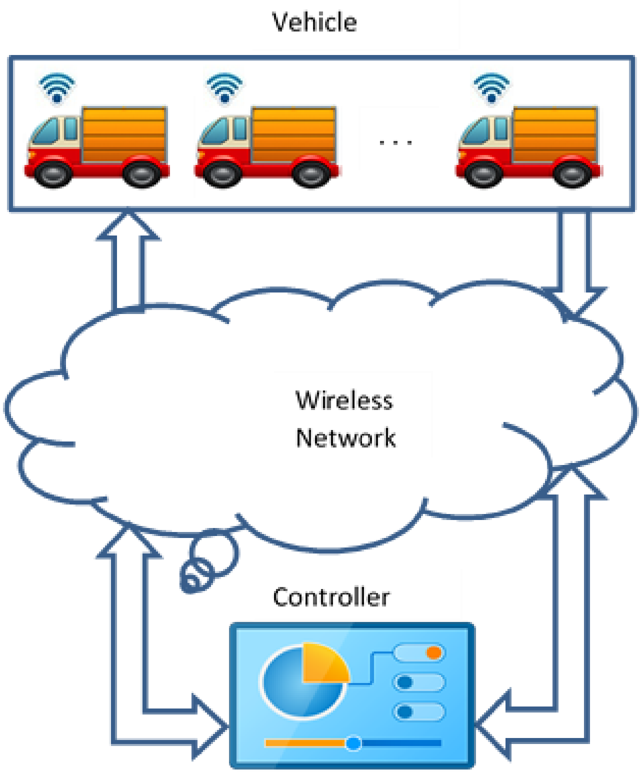

Fig 1: Cyber physical vehicle platoon architecture

CACC is a dynamic algorithm which expertly blends three existing technologies, conventional cruise control (CCC), adaptive cruise control (ACC), and dedicated short-range communication (DSRC). In CCC [13], the underlying vehicle tries to maintain the constant speed despite road grade, wind disturbance, etc. CCC does not take care of any obstacle like vehicles, peoples, corners around it, because of

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this, the driver needs to be aware constantly and takecharge of control when an obstacle arises. ACC [14] vehicles use RADAR, LIDAR sensors which take care of obstruction and can obtain the distance to the preceding vehicle. A completely different technology, where cars move together and form a platoon by keeping safe distance among themselves, is known as cooperative adaptive cruise control [15]. In this technology, states of the vehicles are packed and transmitted to preceding vehicles through the wireless communication [16]. We can also achieve vehicle platoon using ACC [17], but it exhibits oscillations by braking and acceleration in traffic. These oscillations amplify towards the tail of the vehicle string and platoon may lose the string stability. On the other hand, CACC with VANET not only form and maintain a platoon, but also transmit traffic information with adjacent cars, infrastructures and people around, which may improve traffic safety, efficiency, and comfortability [18].

Recently many researchers come up with their work at different level/layers from high-level artificial intelligence to lower level device control of individual device control. Due to lack of proper standard, by seeing growing interest in this field, the Society of Automotive Engineers (SAE) of America come up with six layer architecture from no automation to full automation [19]. Layered architecture of an autonomous vehicle in shown in Fig. 2. In this paper, we are going to illustrate the challenges and solution in layer 5 (full automation layer).

Table 1: Summary of the literature review

Reference	Controller	Control Problem	Spacing Policy	CACC Type
[9]	Sliding mode	Speed regulation	Nonlinear spacing	Homogeneous
[10]	MPC	Gap regulation with predecessor velocity disturbance	Fixed	Homogeneous
[7]	PID	Speed regulation with predecessor velocity disturbance	Constant time headway	Heterogeneous
[11]	PID	String stability	Constant time headway	Homogeneous
[12]	PID	Gap regulation with fuel economy	Fixed	Homogeneous
Our work	Model following control	Gap and speed regulation with predecessor velocity disturbance	Constant time headway	Homogeneous

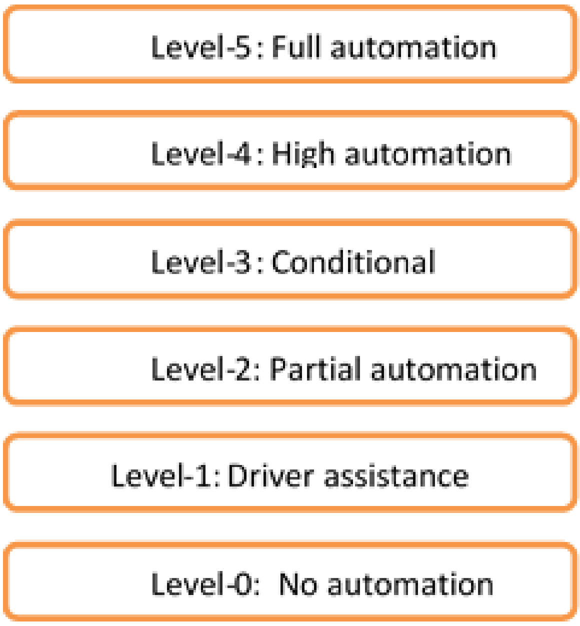

Fig 2: SAE automation levels

The broad problems in CACC are to maintain string stability[20], to enhance road safety, optimising fuel economy[12] and passenger comfort. String stability implies that velocity or spacing disturbances, generated by the platoon leader due to braking and acceleration, should not be amplified towards the tail [2]. String stability is defined using the performance-oriented approach in [21], regarding L p stability properties as defined in [17]. It is shown in [7], CACC has better disturbance attenuation capability than existing ACC. Tomaintain the safety, the number of different spacing policy is considered in literature such as constant spacing (CS), constant time headway (CTH), Quadratic range spacing (QRS), and nonlinear spacing. Practical implementation of CACC depends on dedicated or ad-hoc wireless networks. Despite many advantages, the introduction of a wireless network, communication imperfections are apparent such as Communication delay, packet loss ratio, and limited bandwidth and so on. We have summarised our literature review in Table I.

In this paper, our objective is to control the platoon dynamics and maintain required spacing. A short range wireless communication is assumed with constant delay. Because in this paper, our primary goal is to control the vehicle string, hence we are not concerned about the individual vehicle lower level control. We assumed that lower level control working good which is evident for the realization. Here, we have proposed the model following control to regulate the vehicle string according to highway standard speed.

The paper is structured as follows. In section 2, we described the underlying vehicle model. Controller is designed in section 3. To show the effectiveness of the design, numerical simulation is illustrated in section 4. In section 5, future possibilities is discussed and concluded the paper.

PROBLEM FORMULATION

System Description

The model of the vehicle was determined starting from the following longitudinal motion equation [22]:

$$m\frac{dv_v}{dt} = F_x - mgsin(\theta) - fmgcos(\theta) - 0.5\rho AC_d(v_v + v_w)^2 \qquad (1)$$

where m is the vehicle mass, F_x is the traction force, g is the gravitational acceleration, θ is the road slope, f is the rolling resistance coefficient, ρ is the air density, A is the vehicle frontal area, C_d is the drag coefficient, v_v is the vehicle velocity and v_w is the wind speed. Linearizing equation (1), the model parameters are defined as follows:

$$\begin{aligned} v_v &= v_0 + v \\ F_x &= F_{x0} + u; \\ \theta &= \theta_0 + \theta \end{aligned}$$

we know that,

$$\begin{aligned} sin(\theta_0 + \theta) &= sin\theta_0 cos\theta + cos\theta_0 sin\theta \\ cos(\theta_0 + \theta) &= cos\theta_0 cos\theta - sin\theta_0 sin\theta \end{aligned} \qquad (2)$$

$$(v_0 + v + v_w)^2 = (v_0 + v_w)^2 + 2*(v_0 + v_w)*v \qquad (3)$$

by equation 3 and 1

$$\begin{aligned} m\frac{dv_v}{dt} = F_{x0} + u - mg\left(sin\theta_0 cos\theta + cos\theta_0 sin\theta\right) - \\ \ldots fmg\left(cos\theta_0 cos\theta - sin\theta_0 sin\theta\right) - \\ \ldots 0.5\rho AC_d[(v_v + v_w)^2 + 2\left(v_0 + v_w\right)v \end{aligned}$$

small θ assumption

$$\begin{aligned} sin\theta &\approx \theta \\ cos\theta &\approx 1 \end{aligned}$$

Then,

$$\begin{aligned} m\frac{dv}{dt} = F_{x0} + u - mg(sin\theta_0 *1 + cos\theta_0 *\theta) - \\ \ldots fmg(cos\theta_0 *1 - sin\theta_0 *\theta) - \\ \ldots 0.5\rho AC_d[(v_v + v_w)^2 + 2(v_0 + v_w)v \end{aligned} \qquad (2)$$

$$\begin{aligned} m\frac{dv}{dt} = F_{x0} + u - mg(sin\theta_0 + cos\theta_0 *\theta) - \\ \ldots fmg(cos\theta_0 - sin\theta_0 *\theta) - \\ \ldots 0.5\rho AC_d[(v_v + v_w)^2 + 2(v_0 + v_w)v \end{aligned} \qquad (3)$$

$$\begin{aligned} m\frac{dv}{dt} = F_{x0} + u - mgsin\theta_0 - mgcos\theta_0 *\theta - \\ \ldots fmgcos\theta_0 + fmgsin\theta_0 *\theta - \\ \ldots 0.5\rho AC_d(v_v + v_w)^2 - \rho AC_d(v_0 + v_w)v \end{aligned} \qquad (4)$$

Let,

$$\begin{aligned} &u_f = F_{x0} + u - mgsin\theta_0 - fmgcos\theta_0 - 0.5\rho AC_d(v_v + v_w)^2 \\ &\Gamma = \rho AC_d\left(v_0 + v_w\right) \\ &w_v = mg\left(fsin\theta_0 - cos\theta_0\right)\theta, \\ &\tau_v = \left(m/\left(\rho C_d A\left(v_0 + v_w\right)\right)\right), \\ &K_v = \left(1/\left(\rho C_d A\left(v_0 + v_w\right)\right)\right). \end{aligned}$$

then we can write Eq. 6as

$$m\frac{dv}{dt} = u_f + w_v - \Gamma v \qquad (5)$$

Here for the sake of simplicity,we are assuming the flat surface of highway, so that we can take θ as zero, and w_v can be neglected. $F_{x0} = mgsin\theta_0 + fmgcos\theta_0 + 0.5\rho AC_d(v_v + v_w)^2$, then $u_f = u$ .Now the Eq. 7 can be written in state space form as

$$\frac{dv}{dt} = \dot{v} = \left[\frac{-\Gamma}{m}\right]v + \left[\frac{1}{m}\right]u$$

$$\dot{v} = pv + qu \qquad (6)$$

Where, $p = \left[\frac{-\Gamma}{m}\right]$ $q = \left[\frac{1}{m}\right]$

Which are known by individual vehicle, and these parameter can be transmitted if desired.

We assumed wireless link as the medium of information flow; one can form either V2V or V2I network among vehicles or base stations or roadside units[6]. Wireless link is considered as delay-prone, i.e. it takes some time to deliver states to the preceding vehicle after some time. We considered that a VANET has already been set up and used for states transmission. Now, we will design a controller and investigate the dynamics of VANET- enabled platoon under above consideration, which is a common scenario on a highway.

CONTROLLER DESIGN

Suppose that, we have known reference model of self-driving car which captures the desired behavior for longitudinal motion on flat road is given as

$$\dot{v}_r = av_r + br \qquad (7)$$

where, r represent reference input, v_r is the state of reference model and $a,b \in R,(a < 0, b \neq 0)$ are the known parameters of the reference model at controller side. Now our objective is to design an controller so that car track the velocity of the reference model i.e. $v(t) \to v_r(t)$ .Here we can define error dynamics ($e(t)$) as

$$e = v - v_r$$

Differentiating both side,

$$\dot{e} = \dot{v} - \dot{v}_r \qquad (8)$$

By Eq. 8, 9, 10

$$\dot{e} = pv + qu - av_r - br \qquad (9)$$

here we have designed a state feedback controller as,

$$u = k_1 v + k_2 r \qquad (10)$$

here, k_1 and k_2 are controller gains to be designed. by Eq. 11 and 12,

$$\dot{e} = pv + q\left(k_1 v + k_2 r\right) - av_r - br$$

$$\dot{e} = (p + qk_1)v + (qk_2 - b)r - av_r \tag{11}$$

Let,

$$\begin{aligned} p + qk_1 &= a \\ qk_2 &= b \end{aligned}$$

Then,

$$\begin{aligned} k_1 &= \frac{a-p}{q} \\ k_2 &= \frac{b}{q} \end{aligned}$$

Here, we can write Eq. 13 as,

$$\dot{e} = ae \tag{12}$$

As we know that, as per the reference model $a < 0$, which implies that $e(t) \to 0$, as $t \to \infty$. It proves asymptotic stability of the system. Hence objective is achieved.

RESULTS AND SIMULATION

Let us assume a scenario, there are four homogeneous vehicles in the platoon formation equipped with wireless transmitter and receiver as given in [6]. These cars are able to build an ad-hoc network in real time. As shown in Fig 1, the controller is situated on infrastructure where it acts as virtual leader or it can be placed at leader vehicle also. In this simulation, we considered that controller is placed on cyber infrastructure. The parameters for reference vehicle are considered as a= -0.05, and b= 1*10-3. Whereas we considered homogeneous platoon in which all vehicle have same parameter but not necessarily as reference vehicle model, here we have considered p= - 0.054 and q= 9.09*10-4. We have set the platoon speed at 20 m/s and initially vehicles are placed 10 meter apart from each other. We have considered the multi-hop transmission of packet, and each hop has 10ms delay. As shown in Fig. 3, we have considered that platoon leader is running at constant speed, and all the preceding vehicles are trying to adapt leader's velocity profile. We can clearly see that all the follower tracking leaders effectively. In Fig.4, we can see the initial spacing of 10 meter, and according to CTH policy, velocity dependent spacing is being maintained.

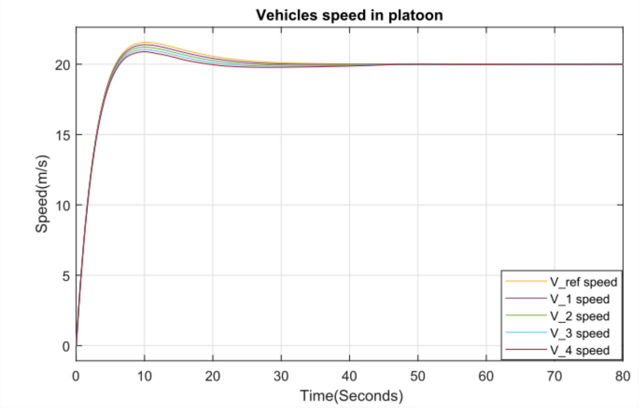

Fig 3: Vehicle speed in platoon

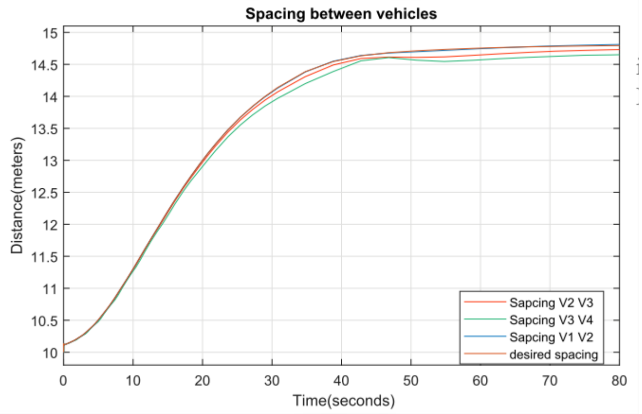

Fig 4: Spacing between vehicles

CONCLUSION

In this paper, we have introduces a high-level linearised model of a vehicle which forms platoon together. The vehicle model plays a significant role in the design of controller and real-time platoon management. Dedicated Short Range Communication (DSRC) is the primary ingredient in CACC enabled systems to overcome the physical limitations of onboard sensors and enables to form string-stable platoons with small inter-vehicle distances. Then a model following controller is proposed in such a way that all the individual entity participating in the vehicle string follow the reference model. Controller design depends on system parameter, which is the limitation of this design in the future one can extend the design of controller which is independent of a system parameter.

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