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Effects of Communication on the Performance of Cooperative Adaptive Cruise Control

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***Abstract:** Advancement 5G communication technology paves the way for inter-vehicle communication like V2V or V2I. These technologies gave direction for future transportation system such as Cooperative Adaptive Cruise Control (CACC). In this article, we will analyse and show the effects of network issues on the performance of individual vehicle and CACC. We will do sensitivity analysis for delay variation. We will study time delay approximation technique and validate with the original system. Numerical simulation is done in MATLAB and Python environment to validate the theoretical analysis.*

***Keywords:** Cooperative adaptive cruise control, Time delay, Performance evaluation, Networked control system.*

I. INTRODUCTION

Among the various transportation infrastructure, ground transportation is the densest and unsystematic. In the most populated Asian countries like India and China, road traffic is a common problem in day to day life. Due to lack of experience and perception ability of human drivers, it is challenging to maintain proper speed and inter-vehicle distance among vehicles [1]. With large scale urbanisation, road infrastructure development and logistics connectivity, a large number of vehicle are on highway. According to Jia et. al. [2], there are more than one billion vehicles worldwide travels on roads and it will be doubled in 10-20 years. Therefore, it is much needed to make smart, intelligent and systematic system which can increase road throughput, safety, fuel efficiency and reduces travel time. In the recent past, various intelligent transportation system (ITS) and related technologies are being researched extensively. One of the accessible technology among connected vehicle technologies is CACC [3]. It is an extension of currently used adaptive cruise control. ACC enabled vehicles use local sensors, to percept their surrounding environment, which has limited capability. The general architecture of CACC is shown in Fig.1. In cooperative adaptive cruise control (CACC) system, vehicles are grouped and form a platoon. In this system, each vehicle regulates its speed and tracks lead vehicle while maintaining the safe the distance across the string [4]. There are Various spacing policies, such as Constant Distance (CD), Constant Time Headway (CTH), Bidirectional (BD), etc., proposed by researchers recently. We can utilise information exchange for various purpose among the vehicles using wireless channels. It forms vehicle to vehicle(V2V) and vehicle to infrastructure(V2I) network. Despite the many advantages, wireless links are prone to some network effects which can deteriorate the performance of the closed-loop system [5].

Several significant work has been published by research community in this direction. Few of them are worth mentioning. Researchers are exploring CACC from various points of view, such as communication perspective [6], [7], control perspective[8], platoon management [9] and drivers charateristics[10] . Homogeneous platoons are analysed by onsu et.al. [11]. In a homogeneous platoon, all the participated vehicles are of the same configuration. Heterogeneity can come from participated vehicles are of different parameters, driver characteristics, spacing policies, information transmission topology. String stability analysis of heterogeneous CACC is done by wang et. al. [12]. A few experimental work and performance evaluation of CACC is shown in [13], [11], [14], [15]. The limitation of most of the state-of-art work is that individual string stability of the platoon has been studied for homogeneous platoons with ideal communication Scenario. However, the delay, packet loss and jitter are common issues in the communication channel. Development of the fast network and communication technology gives rise to distributed and decentralised control system. Different network aware CACC model has been given in [16], [17]. Cyber physical architecture for CACC has been discussed in [2], [18], [1]. The purpose of this paper is to study the effects of network issues on the performance of the closed-loop dynamics of the individual vehicle as well as a platoon. We analyse sensitivity under delay variations.

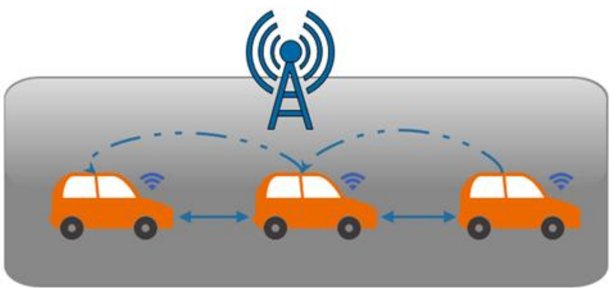

Fig 1: General architecture of CACC

Rest of the paper is organised as follows: We formulate our problem in Section 2, where vehicle model, network assumptions and objectives are given. Design and analysis techniques are described in Section 3. Model parameters and simulation results are shown in Section 4. Lastly, we discussed future research direction and concluded our work in Section 5.

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II. PROBLEM FORMULATION

2.1. Modeling of the Vehicle

In the CACC system, each vehicle is treated as a node and form a horizontal string. Each node is responsible for individual stability and string stability. Here, for vehicle dynamics, we are considering a simple linear point mass model which is shown in Fig. 2.

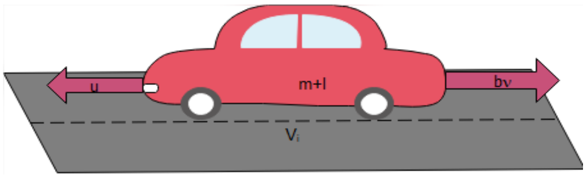

Fig 2: Vehicle mathematical model

Let's suppose, each node has own mass m (in kg) and carrying payload l (in Kg). To move this mass in a longitudinal forward direction, a traction force F (in N) is generated using DC series motor by applying the PWM signal. So $\%_{\text{duty cycle}}$ will act as a control input u and F_p(in(N / $\%_{\text{duty cycle}}$)) is the thrust parameter. We assumed all the resistive force, such as rolling resistance and wind drag, varies linearly in the opposite direction of motion. By the Newton's second law of motion, we can form a force balance equation as,

$$(m+l)\dot{v} + bv = F_p u \qquad (1)$$

Here, we are measuring the speed of the vehicle so,

$$y = v \qquad (2)$$

By rearranging the Eq. 1 and Eq. 2, we can write in statespace form as,

$$\dot{v} = \left[\frac{-b}{m+l}\right][v] + \left[\frac{F_p}{m+l}\right][u] \qquad (3)$$

2.2 Modelling of networked issues

In a CACC string, each vehicle is connected over either V2V or V2I network. This network formed using wireless links for information exchange. Apart from many advantages, there are some bottlenecks due to the introduction of the network in a closed loop dynamic system. Network introduces delay, information loss, jitter in the system. In control system perspective, delayed information is not usable for control input calculation, so delayed packets need to be discarded. Information loss can be seen as delay. Jitter can be removed using the buffer. This buffer considered as slack time in the dynamic system. So for this real-time cyber physical system, all these delays accumulated and form a non-distorting transport delay, which is nothing but the time shift in control input. Controlling such dynamics is challenging because delays cause linear phase shifts that limit the control bandwidth and affect closed-loop stability. In this scenario, there are mainly four types of delay which are sensor-to-controller (τ_{sc}), Computation delay (τ_c), slack time(τ_s), and a controller to an actuator (τ_{ca}). Because all these delays are the part of the control loop rather than the system itself. That's-why, these delays do not change the shape of the output and control signal, but it shifts the signals. Because of this property we can lump these delay together into a single dead time (θ_d) as

$$\theta_d = \tau_{sc} + \tau_c + \tau_s + \tau_{ca} \qquad (4)$$

2.1.1. Assumptions

Here, we have assumed that total round trip delay (θ_d) is constant (slack time can be adjusted to make it constant). Controller and vehicle is able to receive data packet over the network. All the participated nodes are IP enabled. Data packet consists of, speed and other sensor information in feedback loop and control input at forward loop. We assumed that θ_d is upper bounded by θ_d. According to the above assumptions, we can modified Eq. 3 as

$$\dot{v}(t) = \left[\frac{-b}{m+l}\right][v(t)] + \left[\frac{F_p}{m+l}\right][u(t-\bar{\theta}_d)] \qquad (5)$$

For the sake of simplification, we can consider the new variable as

$$\frac{1}{\tau} = \frac{-b}{m+l}; \frac{K}{\tau} = \frac{F_p}{m+l}$$

and by taking the the Laplace transform of Eq. 5

$$\frac{v(s)}{u(s)} = \frac{K.e^{-\bar{\theta}_d * s}}{\tau s + 1} \qquad (6)$$

The objective of this article is to show the effects of the network issues on the performance of individual vehicle and CACC system in a close loop.

III. METHODOLOGY

The standard feedback loop without considering the delayis shown in Fig. 3a and with network consideration is shownis Fig.3b.

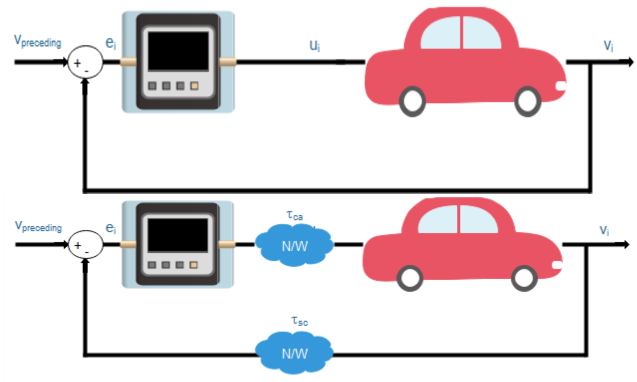

Fig 3b: Close loop control with network

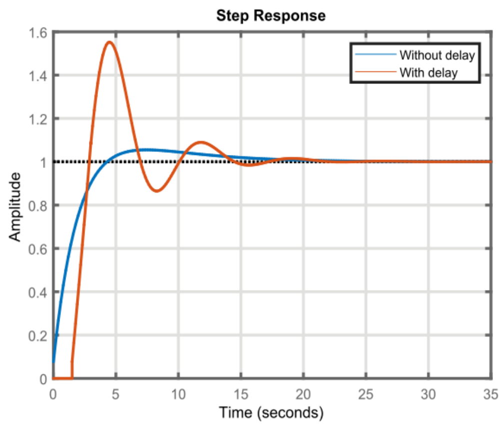

Fig 4:Step Response of unit vehicle

3.1.1. Controller design

To show the effects of network delay in a loop, we are using standard digital PID control algorithm which is given below.

$$u(k) = k_p e(k\Delta t) + k_i \sum_{k=0}^{N} e(k\Delta t)\Delta t + k_d \frac{e_{new} - e_{old}}{\Delta t} \quad (7)$$

PID gains is properly tuned for delay-free case. So for derivative termcalculation, here we need to store the old error value so that when a new error sample come to us e_{old} can be subtracted from e_{new}. For integration, we need to accumulate the error over time which is [$e_{new} = e_{old} + e(k\Delta t)$], where e shows the current packet.Δt term can be associate to the gain term which could be considered in tuning.

3.1.2. Time and frequency domain analysis

The time domain analysis of any dynamical plant to standard signals such as impulse, step, ramp inputs, help us to observe specific characteristics such as rise time (T_r), settling time (T_s), maximum % overshoot, etc. The step response of the vehicle with and without considering the delay is shown in Fig. 4 . Here, we can observe that, delay can produce oscillations, increases maximum overshoot and settling time. This can results collision among vehicles.

By doing the frequency domain analysis, we can find out the robustness and stability margins such as Gain Margin (GM), Phase Margin (PM), Delay margin (DM) and bandwidth of the system. The closed loop frequency response of the system is shown in Fig. 5. We can clearly see gain oscillations in bode magnitude plot due to time delay. Gain margin and Phase margin decreases rapidly as delay increases.

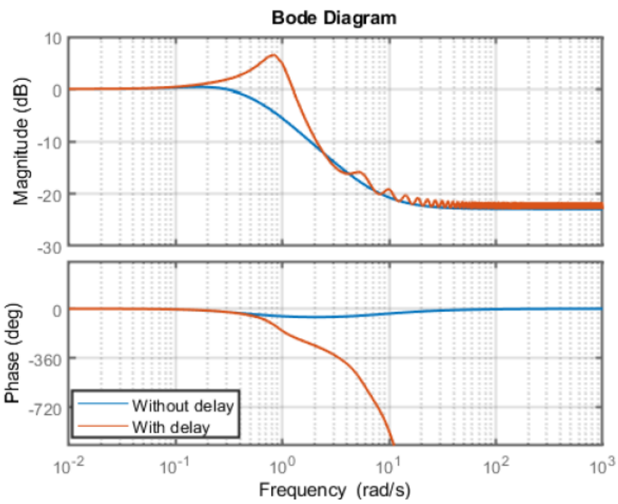

Fig 5: Frequency response plot of a unit vehicle

3.1.3. Sensitivity analysis

In a network, delay occurrence is depend on various factors such as propagation delay, media access delay, etc. so that we rarely know it accurately. Sensitivity of the system with PID controller at various delay values between 0.5 sec to 2 sec is shown in Fig.6. It shows that delay uncertainty has considerable effect on closed-loop step response.

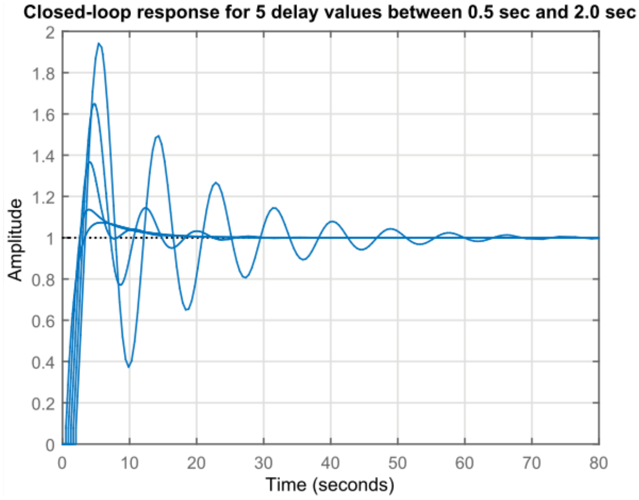

Fig 6: Sensitivity analysis of vehicle response w.r.t. variable delay

3.1.4. Implementation

Many controller design algorithms and close-loop analysis techniques cannot handle time delays directly. A common workaround consists of replacing delays by their Pade approximations. This is valid only at low frequency region, therefore, we need to compare the exact and approximate responses. If there is mismatch in time response, we can increase the approximation order. In Fig. 7, we have compared the exact response with their first and second order Pade approximation. It shows that second order Pade approximation can exactly capture the dynamics of exact delay model. It means that we can use these model for controller design and further analysis. As we go with higher-order Pade approximations, it produces transfer function with clustered poles. These poles are very sensitive to disturbances, that why it is recommended that more than 10^{th} should be avoided.

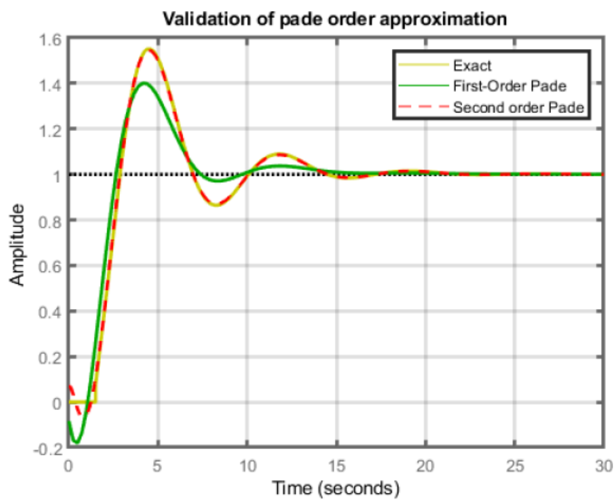

Fig 7: Close loop response of exact and approximate model of unit vehicle

IV. RESULTS AND SIMULATION

For the numerical simulation of CACC two vehicle string, Nominal parameters are tabulated in Table 1.

Table 1: Nominal Parameters

Parameter	Value
Vehicle Mass (m)	500 kg
Payload (l)	200 kg)
Damping coefficient (b)	50 N.s/m
Network delay	2 sec

In this string, one is predecessor vehicle and other one is follower vehicle (More follower can be added). To capture the worse motion scenario which is shown in Fig. 8, we are accelerating predecessor vehicle in sinusoidal manner and follower vehicle tracking this motion. Fig 8a shows velocityresponse in the conventional local close-loop scenario, on the other hand Fig 8b shows the velocity response in cyber- physical environment with delay consideration. We can see that there is a need to consider proper braking distance and velocity limit with consideration of worst case delay otherwise hazardous situation may occur.

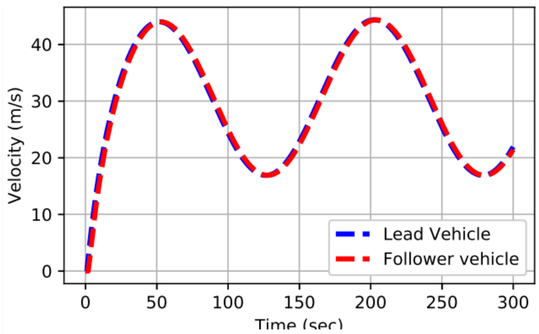

Fig 8a: Velocity response without considering delay

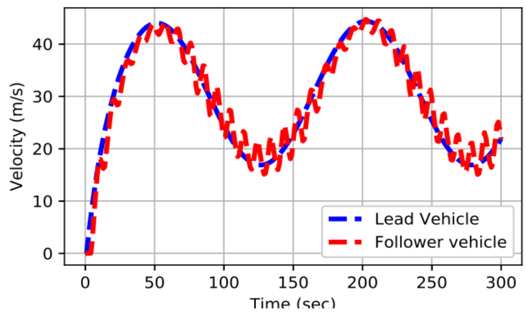

Fig 8b: Velocity response with considering delay

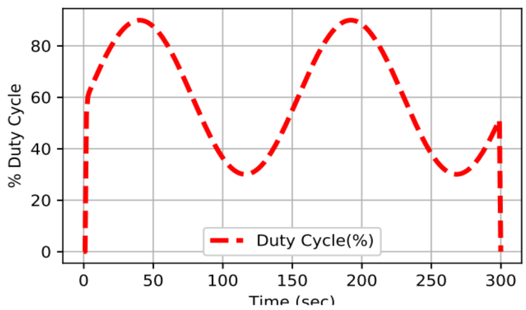

Fig 9a: %Duty Cycle given to predecessor vehicle

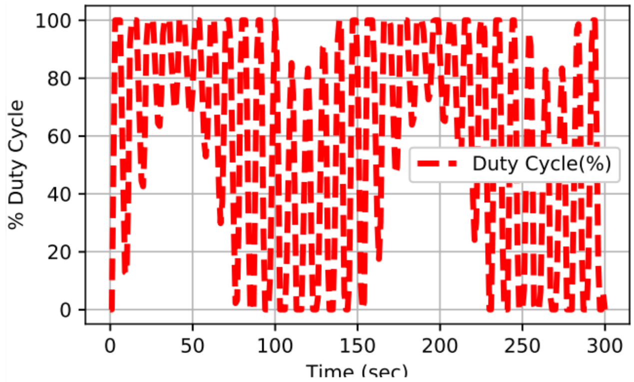

Fig 9b: %Duty Cycle required for tracking

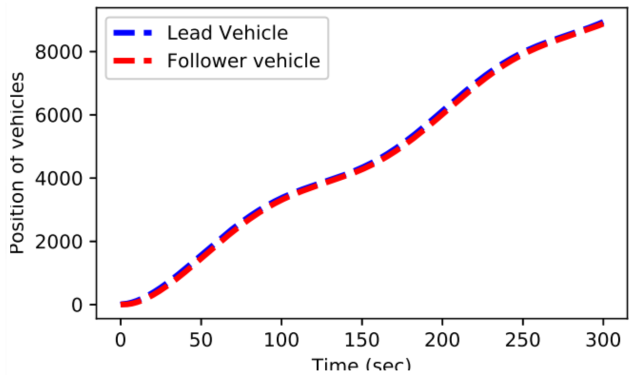

Fig 10a : Position of the vehicle in longitudinal direction without considering delay

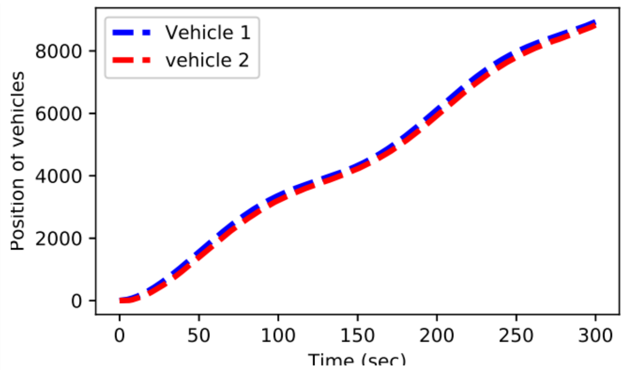

Fig 10b : Position of the vehicle in longitudinal direction considering delay

On the other hand, control input required for tracking under this scenario is shown in Fig. 9b. It is observed that control input is varying too fast. Practically, it is challenging to achieve this control input due to actuator limitation. It can also cause discomfort for passengers. Position of vehicle from starting point in longitudinal direction is shown in Fig. 10

V. CONCLUSION

CACC technology has become a promising future technology to overcome road congestion. It opens the door for intenseresearch in the intelligent and smart transportation system. For the physical implementation and supervisory control, there is a need for decentralised and distributed control to connect smart vehicles. Connections can be established through the wireless V2V and V2I networks. In this paper, we put our view on CACC in the perspective of the cyber-physical system. Firstly, we presented both standard and cyber-physical model of close-loop CACC. The controller is designed for delay- free case to compare the network effects. We emphasised to consider network effects in controller design by delay sensitivity analysis. We showed that without considering these effects, the system could become unstable which results in a deathly casualty. We illustrated the analysis and design techniques of cruise control with delays, Then, we showed effects of network issues on two vehicle string in longitudinal highway motion scenario. In future, we will explore various driving maneuver's and design network-aware controller with stability analysis.

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