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A Platoon Control Method based on Cooperative Adaptive Cruise Control Vehicles in Traffic Flow

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***Abstract*—The increasing number of vehicles are one of the causes of accidents, exhaust pollution and traffic congestion in urban areas. These pressing problems force human to looking for the approach for a higher car flow on highways in less time and with fewer accidents. In that context, one of the approach growing roadway capacity is to make a car/truck grouping moving in a strings in order to follow short distances between the members of the platoon. This approach ensures the simultaneous deceleration or acceleration of all cars in the string. This work gives a control strategy for Cooperative adaptive cruise control (Cooperative ACC) in a platoon through a performance evaluation by simulations. The main goal of platoon control is to stay the desired spacing from front cars of the string using the constant time headway (CTH) policy while keeping the same velocity with the other cars. The results of the numerical example have demonstrated the effectiveness and applicability of the proposed approach for cars platoon.**

***Index Terms*—Cooperative Adaptive Cruise Control, Vehicle Following, Spacing Strategies, vehicle platoon, intelligent transportation systems.**

I. Introduction

In fact, the dramatic increase in the global population joined together the continued increase in the number of car/truck on the roads, it has caused a growing problem in the transportation field, related to traffic congestion and increasing pollution. Traffic congestion is often due poor decisions by drivers or the human driver can not look accurately the behavior of vehicles on the road. Traffic jams not only reduces transportation productivity and fuel consumption, but also increases environmental pollution and human health effects. In that context, these pressing problems force human to looking for the solutions. Traffic congestion may be minimized by increasing traffic, which may be done by decreasing the spacing between cars [1], [2].

However, the driver's reaction time requires a large distance between cars to avoid a collision. A way to decrease the distance between cars is employing driving automation in the longitudinal direction,i.e, in order to reach that, the use of vehicle platooning can stay the vehicle distance, there is no accident risk and velocity is not lost, which then lead to be understood such as an increasing in density of vehicles on the road.

The first idea of the vehicle in the platoon, which is given by [3]: A platoon contains multiple vehicles traveling in close proximity, actively coordinating in formation. In this perspective, this concept is very general, it doesn't give too much communication about how cars/trucks in a platoon are connected to each other and how they must move together in a formation. A more specific and suitable definition, which mentioned the Safe road trains (SRT) for the environment platooning [4]: The formation of a car/truck group in a highway situation is called a vehicle platooning, which includes the leader car/truck and all other cars/trucks that follow the leader by keeping a fixed or variable distance between the member vehicles. The follower cars/trucks in the platoon are controlled autonomously, while the car/truck leading in the platoon is controlled manually to stay a safe environment for the human driver và passengers.

Due to the aforementioned benefits of vehicle group, domestic and foreign scholars from the car manufacturer and research institute is activated conducting on developing platooning strategies. A brief introduction to several of projects about vehicle formation is discussed in [5]. Several projects address the vehicle group concept, the most well known of which are: SRT for the environment of Europe [6], California Partners for Advanced Transit and Highways project in United States [7]. The development of platooning strategies depends on many different factors, for example string stability, distance policy, control target, communication systems.

In this paper, vehicle platooning can be thought as an application based on the CACC technology, which is an advance of the ACC system. More details, it is referring to making a group of vehicles to move in the same way (same velocity, acceleration, spacing etc). Vehicles in a platoon use sensors such as radar and V2V communications.

Cooperative ACC vehicle in a platoon is developed based on the adaptive cruise control (ACC) system by adding information data between multiple vehicles to improve reactivity. This information is get from the V2V or I2V communication. DSRCs is employed to communicate information between vehicles. The benefit of this Cooperative ACC system is that data un-measurable by sensors, e.g., the preferred velocity of preceding cars/trucks may be taken into account. The added information of the predecessor car/truck or back of the platoon to be informed about the traffic situation ahead of the platoon leader, instead of only acknowledging directly neighbored cars, i.e When the preceding vehicle is about to reduce speed or increase speed, the information can be immediately passed on to vehicles following in the platoon, then the vehicles following can react more quickly to the changes, so it does not need to wait for sensor data to confirm pressing the brake or accelerator and can thus respond earlier.

Several papers have been published in the topic of ACC system and more recently with Cooperative ACC system. For example, the Adaptive Cruise control system for the string of cars is one of the most important applications in the ADASs which decreases the time allowed on the road, as well as stays small inter-car spacing between cars using only sensors as radar, laser or cameras [8], [9]. Spacing policies used the most commonly to adjust the spacing between cars/trucks, consisting of the CS policy (see [10], [11], etc) and the CTH policy (see [12], citewu2020spacing, etc). A platoon with the CS policy imply that the desired spacing between members in a platoon is fixed and independent of the speed of preceding. While in the CTH policy, the desired spacing is proportional to its speed, and that is called the time headway h_i. The distance in both policies is determined by measuring device mounted on its front bumper to the rear bumper of the preceding car/truck. Some papers show that the authors mainly considered the constant time headway policy using different approaches such as the LQIR method in [13], SMC in [11], MPC in [14]. The operation of the CACC system affects on V2V communication through technologies: the vehicular ad-hoc networks. In the presence of V2V communication, the information transiting/receiving describes the connectivity of the Cooperative ACC system of cars [15].

Unlike the previous studies [16], the primary contribution of this work gives the design of a Cooperative ACC system for a string of cars that is employed the V2V wireless communication. Only the information with the directly preceding car is considered, with the advantage that if information does not work, the function of standard Adaptive Cruise control will be active. A platoon is to follow the preceding car at a desired spacing that depends on the car speed. The spacing policy relates the desired inter-car spacing via the constant time headway policy. The leader car is presented by the CC system with the desired of the CL system is the desire speed, employing a using a PID controller. The followers car in a platoon gives a spacing control algorithm for the Cooperative ACC system using the constant time headway policy with two controllers, consisting of a feed-back Adaptive Cruise control controller and a feed-forward Cooperative ACC controller. The followers car employ onboard radar mounted on the front bumper of each car to measure the spacing between two consecutive pairs of cars, which are employed in feed-back ACC controllers. The preceding car velocity is available through V2V and is employed by a feed-forward Cooperative ACC controller. The delay in the signal being communicated is taken into account in simulation.

The next part of this study is as follows. In Section II establish the vehicle model. In Section III, we describe the CC controller design for the leader car. In Section IV design the control algorithm for the followers car. And then, simulations to confirm the theoretical results is presented in Section V. Finally, Section VI we get the conclusion.

II. Vehicle Model

A platoon of cars is considered as described in Fig.1, and assumption that the operation of each followers installed with the Cooperative ACC system look at only one preceding vehicle with a leader and N followers, indexed $0, 1, ..., N$ with main types of information flow topology is the predecessor following. The Cooperative ACC structure was discussed and is represented in Fig.2.

The car dynamics was calculated starting from the following longitudinal motion equation [17]:

$$m\frac{d\nu(t)}{dt} = F - F_{br} - F_a - F_r - F_g \tag{1}$$

Where, the car body is subjected to longitudinal forces acting on the car, such as Section force for tyre-road F, braking forces at wheels F_{br}, Aerodynamic drag in the longitudinal direction F_a, the rolling resistance coefficient F_r, gradient resistance F_g.

Resistance forces are defined as:

$$\begin{aligned} F_a &= 0.5\rho_\nu A_\nu C_\nu(\nu+\nu_w)^2 \\ F_r &= C_r m g_\nu \cos\gamma_\nu \\ F_g &= m g_\nu \sin\gamma_\nu \end{aligned} \tag{2}$$

$$F_0 = 0.5\rho_\nu A_\nu C_\nu(\nu_0+\nu_w)^2 + C_r m g_\nu \cos\gamma_0 + m g_\nu \sin\gamma_0 \tag{3}$$

where m is the mass of the car. C_ν, C_r are the aerodynamic drag coefficient, the rolling resistance coefficient, respectively. A_ν is the windward area of the car, ρ_ν is the air density, g_ν is the gravitational acceleration, γ_ν is the road inclination angle, ν is the forward velocity, ν_w is the wind velocity.

The above equation is nonlinear in the forward speed ν, linearization may be made by applying first-order Taylor approximation around the equilibrium point, when $\frac{d\nu(t)}{dt} = 0$. At equilibrium, Eq.1 can be solved for [17]:

where F_0 may be found using assume reasonable values for ν_0, γ_0.

Then the linearized model becomes as follows:

$$\varsigma\dot{\bar{\nu}} + \bar{\nu} = K(u+\chi) \tag{4}$$

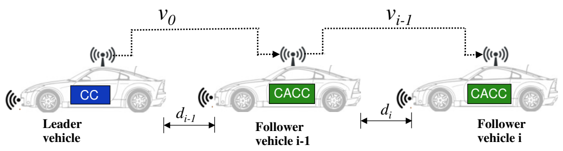

Fig. 1. Structure of vehicle platoon with the CACC system

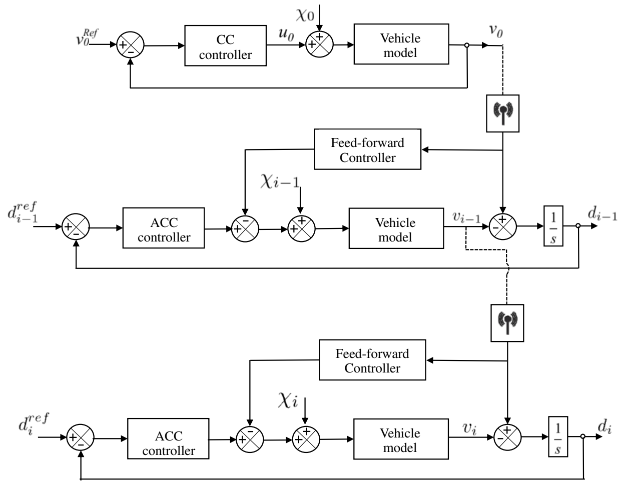

Fig. 2. The control structure of the Cooperative ACC system

where the perturbed variables are determined as, $\bar{\nu} = \nu - \nu_0$, $u = F - F_0$, $u = F - F_0$, $\gamma = \gamma_\nu - \gamma_0$, the parameters ς, K, and χ are determined as follows,

$$\begin{aligned} \varsigma &= m/(\rho_\nu A_\nu C_\nu(\nu + \nu_w)^2) \\ K &= 1/(\rho_\nu A_\nu C_\nu(\nu + \nu_w)^2) \\ \chi &= m g_\nu (C_r \sin\gamma_0 - C_r \cos\gamma_0)\gamma \end{aligned} \quad (5)$$

Using the Laplace transform for Eq.4, The transfer function of the closed-loop system for spacing error between two successive cars pairs is man be represented by:

$$\Xi(s) = \frac{K}{\varsigma s + 1} \quad (6)$$

III. Controller design for leader vehicle

For the CC systems, it builds a more realistic car model by considering the throttle dynamics, i.e adjusts the input of throttle based on a DC motor introduced by Tsujii et al. [18]. Thus, a motor throttle actuator model is presented as:

$$\Xi_a(s) = \frac{K_a}{s(\varsigma_a s + 1)} \quad (7)$$

where the function of the motor-drive duty cycle is the input and the function of the tractive force is the output.

The leader ($i = 0$) is to regulate the car speed so that it follows and stays the desired speed by the driver's command.

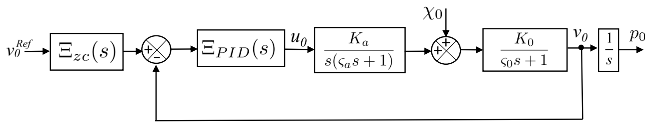

Fig. 3. Car platoon leader control structure with the proportional–integral–derivative controller

The reference for the CL system is the desired speed. The controller of the CC system is used a PID controller (as shown in Fig.3) with the transfer function can be written in the form:

$$\Xi_{PID}(s) = K_P + \frac{K_I}{s} + K_D s \quad (8)$$

In this controller, we present an alternative design approach via the pole placement. First, the CL transfer function considering the PID expression Eq.8, the longitudinal car model Eq.6, and actuator model Eq.7 is the following:

$$\Xi_0(s) = \frac{\frac{K_D K_a K_0}{\varsigma_a \varsigma_0} s^2 + \frac{K_P K_a K_0}{\varsigma_a \varsigma_0} s + \frac{K_I K_a K_0}{\varsigma_a \varsigma_0}}{s^4 + \frac{\varsigma_a + \varsigma_0}{\varsigma_a \varsigma_0} s^3 + \frac{1 + K_D K_a K_0}{\varsigma_a \varsigma_0} s^2 + \frac{K_P K_a K_0}{\varsigma_a \varsigma_0} s + \frac{K_I K_a K_0}{\varsigma_a \varsigma_0}} \quad (9)$$

The controller only have three design variables (K_P, K_I and K_D) while the CL characteristic polynomial has four poles, we may place only three of the four CL poles. Then, the forth pole is defined by the fixed coefficient ($\frac{\varsigma_a + \varsigma_0}{\varsigma_a \varsigma_0}$) of the CL characteristic equation.

The remaining three poles are chosen through the overshoot and the time response. The CL characteristic equation then become:

$$\begin{aligned} &(s^2 + 0.6s + 0.1)(s + 0.4)(s + \frac{\varsigma_a + \varsigma_0}{\varsigma_a \varsigma_0} - 1) = \\ &\quad s^4 + \frac{\varsigma_a + \varsigma_0}{\varsigma_a \varsigma_0} s^3 + (\frac{\varsigma_a + \varsigma_0}{\varsigma_a \varsigma_0} - 0.66)s^2 + \\ &\quad (0.34\frac{\varsigma_a + \varsigma_0}{\varsigma_a \varsigma_0} - 0.3)s + 0.04(\frac{\varsigma_a + \varsigma_0}{\varsigma_a \varsigma_0} - 1) \end{aligned} \quad (10)$$

The PID parameters to achieve these pole assignments determined from Eq.10 are:

$$\begin{aligned} K_P &= \frac{0.34(\varsigma_a + \varsigma_0) - 0.3\varsigma_a\varsigma_0}{K_a K_0} \\ K_I &= \frac{0.04(\varsigma_a + \varsigma_0) - 0.04\varsigma_a\varsigma_0}{K_a K_0} \\ K_D &= \frac{\varsigma_a + \varsigma_0 - 0.66\varsigma_a\varsigma_0 - 1}{K_a K_0} \end{aligned} \quad (11)$$

The CC controller proposes two zeros to the C-L transfer function that growing up the control system overshoot. Two zeros proposed by the PID controller may be compensated by giving two zero-cancellation block as in Fig.3 in the feed-forward path. A transfer function takes the form as below:

$$\Xi_{zc}(s) = \frac{\frac{K_I K_a K_0}{\varsigma_a \varsigma_0}}{\frac{K_D K_a K_0}{\varsigma_a \varsigma_0} s^2 + \frac{K_P K_a K_0}{\varsigma_a \varsigma_0} s + \frac{K_I K_a K_0}{\varsigma_a \varsigma_0}} \quad (12)$$

IV. COOPERATIVE ACC SYSTEM DESIGN FOR FOLLOWER VEHICLE

The block diagram of follower car employing the Cooperative ACC system is illustrated as Fig.4. The main control objective of followers equipped with the Cooperative ACC system is to guarantee maintain the desired spacing to the corresponding preceding car defined by the spacing policy, while maintaining the same velocity as the leader, i.e.

$$\begin{cases} \lim\limits_{t\to\infty} \|\delta_i(t)\| \to 0 \\ \lim\limits_{t\to\infty} \|\nu_i(t)\| \to \nu_{i,ref}(t) \end{cases} \quad (13)$$

Using the CTH policy is getting increasingly popular in a platoon, which is one of the spacing policies used most commonly and it has been mentioned in [2], [19], [20]. Through the CTH policy, the desired inter-car distance between the preceding car and the following car:

$$d_i^{ref}(t) = c_0 + T_d \nu_i \quad (14)$$

where the constant c_0 and T_d are the minimal safe inter-car distance (at zero velocity) and the time gap, respectively, l_{i-1} is the car length.

Define the measured inter-car distance between two consecutive pairs is follows as:

$$d_i(t) = p_{i-1} - (p_i + l_{length}) \quad (15)$$

The spacing errors for the CL system between two consecutive pairs is defined in the form:

$$\delta_i(t) = p_{i-1} - p_i - l_{length} - c_0 - T_d \nu_i \quad (16)$$

The system of the follower car has two controllers, consising of a a feed-back Adaptive Cruise control controller for staying the desired spacing between two consecutive pairs and a a feed-forward Cooperative ACC controller to compensate the effect of the measurable disturbance. The desired spacing is kept by the Adaptive Cruise Control controller. Considering the possibility of V2V failure, the Adaptive Cruise Control controller are used the two integrals of the error since it is assumed that the speed of the lead car that acts as a disturbance to be rejected by the control law can be modeled as as a ramp-type signal input. Thus, the double integrator is integrated in the control algorithm, the followers car may follow the lead vehicle even when it accelerates/decelerates. The need for dual integrator made the employ of a proportional–integral–derivative controller impossible. Considering this aspect, a state-based control algorithm with a double integrator was employed for the Adaptive Cruise Control controller.

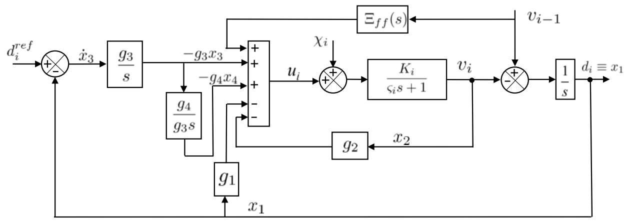

Fig. 4. The control system structure for a follower car

A feedback controller for this system is obtained through the following state equations:

$$\begin{aligned} \dot{x}_1 &= -x_2 + \nu_{i-1}, \\ \dot{x}_2 &= -(1/\varsigma_i)x_2 + (K_i/\varsigma_i)(u_i + \chi_i), \\ \dot{x}_3 &= d_i^{ref} - d_i, \\ \dot{x}_4 &= x_3 \end{aligned} \quad (17)$$

In which, the measured values $x_1 = d_i$ and $x_2 = v_i$; x_3, the integral of the error, $\delta_i = d_i^{ref} - d_i$; and x_4, the double integral of the error. The state based controller yields:

$$u_i = -g_1x_1 - g_2x_2 - g_3x_3 - g_4x_4 = g^T x \quad (18)$$

where, $g^T = -[g_1 \quad g_2 \quad g_3 \quad g_4]$ and $x = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$. The controller gains, g^T may be obtained by a variety of approachs, and a pole-placement design technique is utilized in the MATLAB software.

The feed-back Adaptive Cruise control controller is used to decrease the effect of the measurable disturbances or rejecting the measurable disturbance, and is obtained by taking the inverse of the longitudinal vehicle model Eq.6:

$$\Xi_{ff}(s) = \Xi_i^{-1}(s) \quad (19)$$

the inverse of the transfer function Eq.6 may be approximated due this inverse is not realizable:

$$\Xi_i^{-1}(s) \approx \frac{1 + s\varsigma_i}{K_i(1 + s\varsigma_i/\bar{\chi})} \quad (20)$$

where $\bar{\chi}$ is the frequency range for which the inversion is valid.

The state model Eq.17 of the followers car i is rewritten in the form:

$$\begin{aligned} \dot{X} &= AX + B^T U + GW \\ Y &= CX \end{aligned} \quad (21)$$

where the matrices, vectors, respectively:

$$A = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & -1/\varsigma_i & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}; B = \begin{bmatrix} 0 & K_i/\varsigma_i & 0 & 0 \end{bmatrix}$$

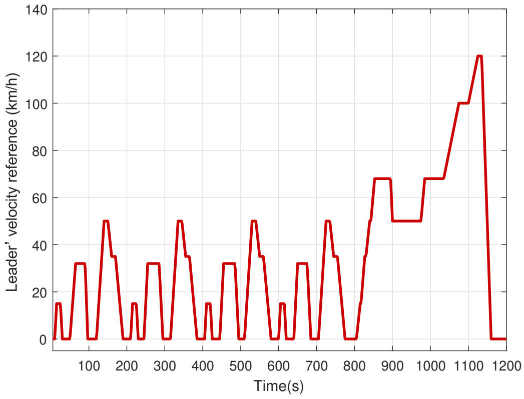

Fig. 5. NEDC (velocity reference)

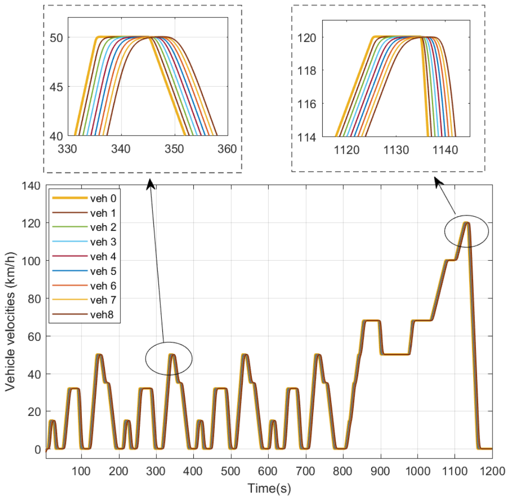

Fig. 6. The velocities of all cars in the string

$$G = \begin{bmatrix} 1 & 0 \\ 0 & K_i/\varsigma_i \\ 0 & 0 \\ 0 & 0 \end{bmatrix}; C = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}; W = \begin{bmatrix} \nu_{i-1} \\ \chi_i \end{bmatrix}$$

Applying Ackermann's formula, the following state feed-back gain matrix can be determined:

$$g^T = [0 \quad 0 \quad 0 \quad 0] R^{-1} P_z(A) \tag{22}$$

Here, $R = [B \quad AB \quad A^2B \quad A^3B]$, $P_z(s) = (s^2 + 2\zeta\omega_n s + \omega_n^2)(s + 4\omega_n)^2$ are respectively the controllability matrix, the characteristic polynomial of the CL system determine through the desired performances.

For the feed-forward controller, which employes V2V technology in order to have the data about the speed of the preceding car. Normally, the communications between members in a platoon is done at every 100 milli-seconds . From this reason, in the controllers where the delay occurs, its maximum value will be 100 milliseconds.

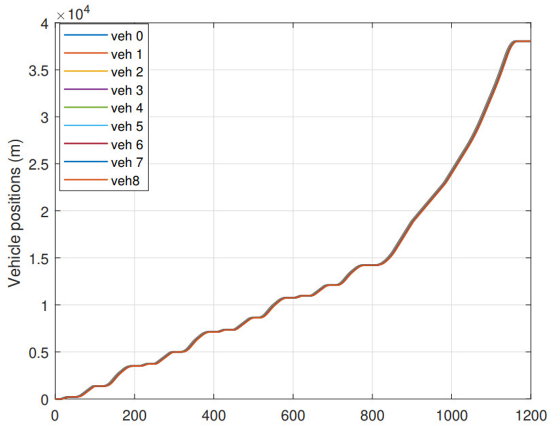

Fig. 7. Vehicle positions of all cars in the string

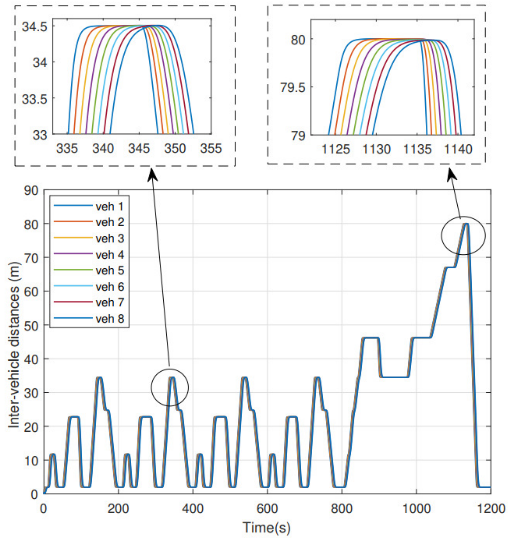

Fig. 8. Distance tracking curve under NEDC condition

V. Numerical Example

In order to achieve the control effect of the Cooperative ACC system for the cars in traffic flow more intuitively, by employing software Matlab/Simulink to evaluate with the last 8 cars followed the first car.

The basic parameters of passenger car model are given as follows (see in [17]):

$$m = 1000kg, C_\nu = 0.5, A_\nu = 1m^2, \ \rho_\nu = 1.202kg/m^3,$$
$$C_r = 0.015, \nu_w = 2m/s, \nu_0 = 20m/sm/s,$$
$$g_\nu = 9.81m/s^2, \gamma_0 = 0, l_{length} = 5m$$

For the leader, the actuator parameters used here are $K_a = 10$ and $\varsigma_a = 0.05s$ [17]. The PID controller's design is done, resulting the tuning parameters $K_P = 28.123$, $K_I = 3.2145$, $K_D = 85.3515$. For the followers, the desired distance is determined according to Eq.14 depending on its vehicle velocity with $c_0 = 2m, T_d = 0.65s$. The ACC controller includes a state feed-back controller with four states, the structure of the ACC controller is employing the pole placement design technique, resulting $g^T = [-3.01 * 10^6 \quad 9 * 10^4 \quad 38.68 * 10^6 \quad 18.439 * 10^7]$. Also, the structure of the feed-forward Cooperative ACC controller was employing Eq.19, Eq.20.

The velocity reference v^{ref} used in this simulation study is the New European Driving Cycle (NEDC) (mentioned in [21]) presented in Fig.5. NEDC cycle consists four urban cycles and one suburban cycle. The average velocity of urban is 19km/h. The average velocity of suburban is 62km/h. The average velocity ofthe whole cycle is 32.12km/ h. The total time are 1200s.

The simulation results of the platoon with proposed controller are indicated as follows:

- In Fig.6, the vehicle velocities together with v^{ref} are illustrated.
- In Fig.7, it is possible to observe the path of the vehicles according to their position along with the total distance traveled.
- Fig.8 depictes the inter-car distances with zooms in two specific areas.

For more details, the velocity signals of each car are described in Fig.6. It may be observed that every car is accelerating and decelerating in order to follow the imposed speed profile.

In Fig.7, the positions of the nine vehicles are at the steady-state, at the same time the collision was avoided.

In Fig.8, the spacing between two consecutive pairs, after a velocity dependent reference is used the input for the control systems are depicted. The desired car spacing determined by fixed time headway will be larger. It may be seen that in this work the spacing wave forms follow the velocity profile applies as reference for the leader.

Specifically, when the vehicle's speed increases, the spacing between two consecutive pairs also increases. This proportionality property is also true when reducing the velocity. It stays excellent spacing tracking and makes the actual car spacing near the expected value at high velocity for better economic performance.

VI. Conclusions

In this study, the platoon control method based on cooperative adaptive cruise control vehicles in traffic flow was presented. The vehilce platoon includes one leader and the followers, in which the leader that is controlled through the Cruise control system since in this study the velocity reference is set up by the driver, the followers in a platoon integrate the feed-back ACC controller and the feed-forward Cooperative ACC controller. This method allows to stay the desired spacing from front cars of the platoon though the CTH policy while keeping the same velocity with the other vehicles.

From the result of the numerical example, the obtained responses depicte that the behavior of the cars in a string is the desired one, i.e. the velocities and the inter-car spacing follow to keep at the reference values.

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