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# A Comparative Study of Adaptive Cruise Control System based on Different Spacing Strategies

**Duc Lich Luu** *,** **Ciprian Lupu** * **Hamid Alshareefi** *

* *Department of Automatic Control and Systems Engineering, University Politehnica of Bucharest, 313 Splaiul Independentei Street, Sector 6, Bucharest 060042, Romania, (e-mail: duc-lich.luu@stud.acs.upb.ro; ciprian.lupu@upb.ro; hamedgep@yahoo.com).*
** *Faculty of Mechanical Dynamics, Vinh University of Technology Education, 117 Nguyen Viet Xuan Street, Vinh City, Nghe an 460000, Viet Nam.*

**Abstract:** Recently, the trend of effective driving research has received more attention, they improve the overall traffic flows and individual driving performances on urban roads, especially at intersections where arterial congestion urban areas causing the decreasing of its capacity, a solution to this problem is to use advanced control systems in the field of intelligent transportation systems (ITSs). In this study, the solution is presented by using the adaptive cruise control (ACC) system of vehicle platoons based on the constant spacing (CS )strategy and constant time headway (CTH) strategy. Simulated the vehicle platoons at the signalized intersection to analyze the advantages and disadvantages of two distance strategies through string stability analysis, improving the urban arterial capacity. Additionally, the smart car prototype in a platoon is introduced and is tested for the ACC system based on the CS strategy with the aim of verifing for the practicability and effectiveness between the theory and the experiment. The proposed approaches were test and simulated and the results were analyzed providing some conclusions related to their efficiency.

*Keywords:* Adaptive Cruise Control, Spacing Strategies, smart car, real time system, vehicle platoon

## 1. INTRODUCTION

Transport systems in the world are becoming a global issue, the continuously growing road vehicles lead to traffic congestion and have a lot of disadvantages such as increased risk of accidents, fuel consumption, pollution, causing discomfort to the driver and passengers, and thus reduce the operating efficiency of cars/trucks. They often build additional highway capacity and city roads. However, this solution has become increasingly difficult and is greatly limited by both concerning money and environmental reasons. Therefore, we need to find an alternative, which is increasingly popular, some approach for modeling urban traffic and eliminate congestion at intersections are demonstrated in Voinescu et al. (2009), Shen et al. (2011). Several other technical approaches to increase existing traffic capacity have been studied in Hasan et al. (2017), Talebpour and Mahmassani (2016), Lioris et al. (2017), Luu and Lupu (2021).

In ITSs, the strategies control of cars/trucks platooning are the solution for this problem which grow to be a popular study area for vehicles because there is much interest in the ACC (see Vahidi and Eskandarian (2003), He et al. (2020)). The ACC system for the platooning of cars/trucks is one of the key task in the ADASs which reduces the allowable headway time, as well as maintains small inter-vehicle distances between vehicles by using only embedded devices such as radar sensors, laser or cameras Guo and Yue (2011), Rajamani and Zhu (2002), Bifulco et al. (2013), Tigadi et al. (2016), Luu and Lupu (2021), Luu et al. (2020b). Therefore, that can be regarded as one approach techniques to decrease traffic congestion, grow traffic safety and decrease emissions without paying any costs. In Darbha et al. (2019), the authors investigated the benefit of wireless methods over non-wireless methods in providing less time headway in vehicle platoons. However, exchange information is really a challenge for platoon performance.

The structure of platoon is understood as the combining of a group of cars/trucks installed the CC system, ACC system, consisting of a leader car/truck and member cars/trucks and keep a formation of a certain shape. The leader car/truck determines the platoon velocity and the followers in a platoon follow the leader or the car/truck ahead with a small headway distance. There are a great deal of scientific literature has been implemented in this field. Address different concerns from different perspectives, we can summarise some important related studies as follows:

Spacing strategies used the most commonly to adjust the distances between vehicles, including the CS strategy (see Darbha et al. (2020), Guo and Yue (2011), Liu et al. (2014), Jia and Ngoduy (2016), Guo and Li (2019), etc) and the CTH strategy (see Ioannou and Chien (1993), Öncü et al. (2014), Bian et al. (2019), Wu et al. (2020), Chehardoli (2020), etc). A platoon with the CS strategy imply that the desired spacing between members in a platoon is fixed and independent of the velocity of preceding. While in the CTH strategy, the desired distance is proportional to its velocity, and that is called the time headway $h_i$. The distance in both strategies is determined by measuring device mounted on its front bumper to the rear bumper of the preceding car/truck. The literature shows that the authors mainly considered the CTH strategy with many different control strategies like the Linear Quadratic Integral Regulator and Generalized Predictive Controller in Tiganasu et al. (2021), Jiang (2020), Sliding Mode Control in Guo and Li (2019), Yu et al. (2018), Model Predictive Control in Ravikumar et al.

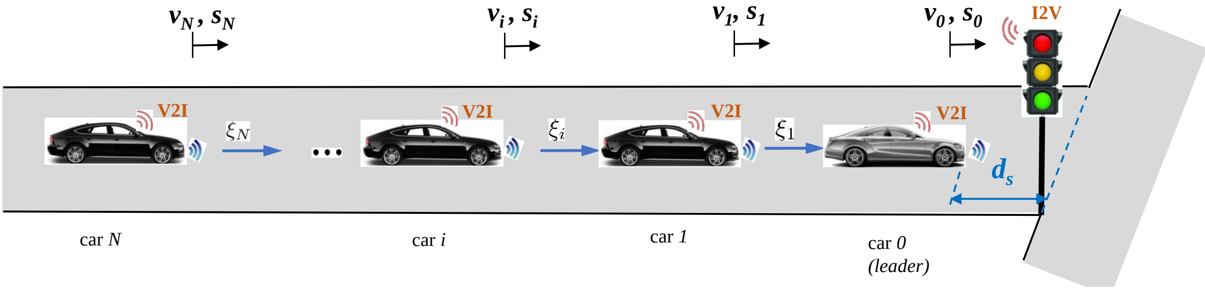


Fig. 1. Schematic diagram of platoon with N car formed into an intersection

(2018), Takahama and Akasaka (2018), Lin et al. (2021), Mazzola and Schaaf (2014). These studies are designed basic ACC controllers from the linearized model. String stability is directly affected by the spacing strategies selected in a platoon, it is claimed in Chehardoli and Homaeinezhad (2018).

For the experimentation: In many studies, Bifulco et al. (2013), Ploeg et al. (2011), Naus et al. (2010), Kianfar et al. (2015), Hu et al. (2020) they have been tested ACC functionalities in a platooning to stay a desired spacing to the preceding car/truck by using the measurement of embedded sensors like radar sensors or laser based on the CTH strategy.

Robot platooning has been interested in recent years, they regard independent vehicles like platforms of mobile robots. This proposed solution is simple to utilize, the authors of Cristescu et al. (2012), Copot et al. (2016), Yu et al. (2017), Trudgen et al. (2018) have been used robot platooning to applied for the ACC with different controllers including predictive controller, sliding mode controller, controller and consider into account for the noise of measuring devices and actuator failures. Some other studies Luu et al. (2019a), Lupu et al. (2018), Mastellone et al. (2008), Luu and Lupu (2019), they have been introduced and implemented mobile robots to keep a formation same time avoiding collisions, spotting people, or a tracking lane system.

The CTH strategy is simulated Luu et al. (2019b), Devika et al. (2019), Bian et al. (2018) and tested in real-time, the details of which are proposed in Wen and Guo (2018), Konduri et al. (2017). The CS strategy is simulated Luu et al. (2020b), Wen et al. (2016), Guo and Yue (2012) and tested in real-time, the details of which are proposed in Luu et al. (2020b), Guo and Yue (2014).

Most theoretical works do not consider the detailed analysis of operating mechanisms and comparative research between two spacing strategies. Especially, evaluating the urban arterial capacity at the signalized intersection for the two distance strategies of the ACC system. In this study, the major contributions differentiating this work from previous studies lie in the following aspects:

Simulate for 21 cars in a platooning through the signalized intersection, in which a leader and 20 followers to automatically adjust the car speed to stay the desired distance between the members of the platoon. The controller of the leader car installed with the CC system is a PD control architecture to follow the desired reference speed. The follower cars in the platoon installed with the ACC system is to stay the desired distance based on the CTH strategy and the CS strategy without wireless inter-vehicle communication. The obtained results compare the characteristics between the CTH strategy and the CS strategy.

Next, test for 04 smart cars as Arduino cars in robot platooning, consisting of one leader - CC system and three followers is equipped with the ACC system based on the CS strategy. Each smart car measures only the distance between itself and the one in front of it by IR sensors. The obtained results will be verified for the effectiveness between the theory and the experiment.

The organizational structure of this study is as follows: In Section 2, mathematical models of vehicles in a platoon and the intersection scenario are established and in Section 3, the design method for a CC system is presented. Section 4 is dedicated to the ACC algorithms. Section 5 introduces the car structure description in robot platooning. Section 6 provides detailed numerical simulations for the ACC system and performance comparisons between under different spacing strategies. Finally, the conclusion and research perspectives are drawn in Section 7.

## 2. MODELING VEHICLES IN A PLATOON

Considering that a platoon of $N+1$ of queued cars at intersection waiting at a red light signal which enables thus to start moving in a coordinated manner once the signal light turns green, and assumption that the operation of each followers installed with the ACC system look at only one preceding car with a leader and $N$ followers, indexed $0,1,...,N$ ( as shown in Fig.1). All cars receive the current phase of traffic signal light at the intersection through I2V communication system and each car are equipped with devices to measure the distance, relative velocity to the preceding car.

Here, the position, velocity, acceleration in longitudinal axis of the leader car at time instant $t$ are indicated by $s_0(t)$, $v_0(t)$, $a_0(t)$, $(i=0)$, corresponding. More detail, $s_i(m)$, $v_i(m/s)$, $a_i(t)$ indicates the position, velocity, acceleration in longitudinal axis of the follower car $i$, $i \in \{1...N\}$, corresponding. $d_s$ is the distance from the leading car to the starting position of the intersection. According to this, the control objective of a platoon (except the leader car) is to follow its corresponding preceding car at a desired distance $\xi_{i,ref}$.

According to Newton's second law, car longitudinal motion modeling is defined (see, e.g., Luu et al. (2020a), Ulsoy et al. (2012) and Rajamani (2011) for details).

$$m_i \frac{dv_i(t)}{dt} = P_{si}(t) - m_i g_v \sin\gamma_v - f_v m_i g_v \cos\gamma_v - 0.5\rho_v A_v C_v v_i^2(t) \quad (1)$$

In which, $m_i$ is the car mass, $P_{si}$ is the traction force provided by the engine. The resistances of car includes air resistance, road friction, ramp resistance, in which $A_v$ is the car frontal area, $C_v$ is the air resistance coefficient, $\rho_v$ is the air density, $f_v$ is the road friction coefficient, $\gamma_v$ is the road slope, $g_v$ is the gravitational acceleration.

Where, the time lag constant of the car is set to $\varsigma_i$, we assume that $\varsigma_i \leq \varsigma_0$ and $\varsigma_0$ is an upper bound on the time lag constant, it can be chosen as $0.5s$. Thus, actual acceleration variation of the car is depicted in the form:

$$\dot{a}_i(t) = \frac{1}{m_i\varsigma_i}[P_{ui}(t) - P_{si}(t)] \tag{2}$$

Bring the equation (1) into the equation (2):

$$\dot{a}_i(t) = \frac{1}{m_i\varsigma_i}[P_{ui}(t) - m_i a_i - m_i g_v \sin\gamma_v - f_v m_i g_v \cos\gamma_v - 0.5\rho_v A_v C_v v_i^2(t)] \tag{3}$$

The expected traction force of the car is applied as:

$$P_{ui}(t) = m_i u_i(t) + m_i g_v \sin\gamma_v + f_v m_i g_v \cos\gamma_v + 0.5\rho_v A_v C_v v_i^2(t) \tag{4}$$

Here $u_i$ is the desired acceleration (control input) to be designed, provided by the controller. Now, substituting equation (4) into equation (3), the longitudinal dynamics of each car in the platoon is described as:

$$\varsigma_i\dot{a}_i(t) + a_i(t) = u_i(t) \tag{5}$$

Then, the dynamic equation of longitudinal dynamic model of the $i^{th}$ car is obtained as:

$$\begin{cases} \dot{s}_i(t) = v_i(t) \\ \ddot{s}_i(t) = a_i(t) \\ \varsigma_i\dot{a}_i(t) = u_i(t) - a_i(t) \end{cases} \tag{6}$$

It is considered that the platoon is homogeneous in this study. The state-space representation of the inter-car longitudinal dynamics is became from equation (6) and maybe rewritten as follows:

$$\dot{X}_i(t) = AX_i(t) + Bu_i(t) \tag{7}$$

(8)

where the matrices, vectors, respectively:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{\varsigma_i} \\ 0 & 0 & 0 \end{bmatrix}; B = \begin{bmatrix} 0 & 0 & \frac{1}{\varsigma_i} \end{bmatrix}^T; X_i(t) = \begin{bmatrix} s_i(t) \\ v_i(t) \\ a_i(t) \end{bmatrix}^T$$

As in Fig.2, the transfer function between desired acceleration and the real longitudinal position of the car model is given by:

$$G_i(s) = \frac{S_i(s)}{U_i(s)} = \frac{1}{s^2(\varsigma_i s + 1)} \tag{9}$$

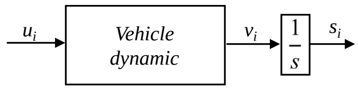


Fig. 2. Block-scheme of the car longitudinal dynamics model

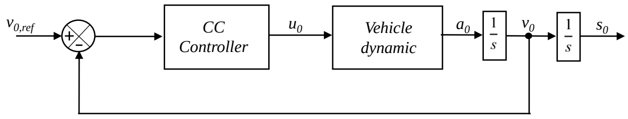


Fig. 3. Block-scheme of the leader car

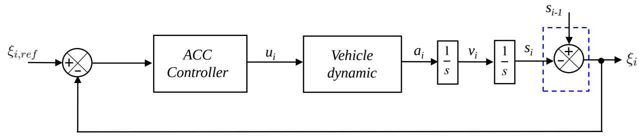


Fig. 4. Block scheme of the n follower car in the platoon

## 3. CC SYSTEM DESIGN FOR LEADER VEHICLE

The leader car is designed by the CC system which is to regulate the car velocity so that it follows and keeps the desired reference velocity by the driver's command. The reference for the closed-loop system is the desired reference velocity. Base on the command signal $v_{0,ref}$ from the human drivers and the feedback signal from the speed sensor.

For the CC system, this system is designed by the PD controller based on the car longitudinal dynamics model equation (9) to regulates car velocity by adjusting to increase or decrease the desired acceleration $u_0$ as in Fig.3 is used.

The CC controller for the leader can be written in the form:

$$G_{cc}(s) = K_p + K_d s \tag{10}$$

where $K_p, K_d$ are respectively the parameters of the algorithm for the CC controller.

## 4. PROPOSED ALGORITHM FOR THE FOLLOWER VEHICLES

The block diagram of a full car employing the ACC system is represented as Fig.4.

The ACC system is one of the applications of the longitudinal control strategy. The leader using the CC system is set to follow the desired reference velocity. The goal of the follower cars equipped with the ACC system is to ensure keep the desired distance to the corresponding preceding car defined by the spacing policies, while maintaining the same speed as the leader, i.e.

$$\begin{cases} \lim\limits_{t\to\infty} \|\delta_i(t)\| \to 0 \\ \lim\limits_{t\to\infty} \|v_i(t)\| \to v_{i,ref}(t) \end{cases} \tag{11}$$

For the follower vehicle, two spacing strategies includes the CS strategy, the CTH strategy schemes is provided to reach string stability and improve the road capacity and there is no wireless inter-car communication.

### 4.1 ACC System Design base on the Constant Spacing Strategy

The ACC system controller only use the measuring device and not dependent on the information of the car or any other form of cooperation involving other cars on the road.

The inter-car distance (actual distance) $\xi_i(t)$ between the car $i$ and its preceding car is measured employing sensor mounted on the front bumper of individual car and it is described as:

$$\xi_i(t) = s_{i-1}(t) - s_i(t) - l_{i-1} \tag{12}$$

where $l_{i-1}$ - the car length. The distance errors for the closed-loop system between two consecutive pairs of cars is as:

$$\delta_i(t) = \xi_i(t) - \xi_{i,ref}(t) = s_{i-1} - s_i - l_{i-1} - \xi_{i,ref} \tag{13}$$

where $\xi_{i,ref}$ is the desired distance between adjacent two cars, it indicates a fixed constant.

In the platoon, length from the leader car to the last car consisting of the length cars and distances between cars is described as:

$$L_{platoon}(t) = s_0(t) - s_N(t) \tag{14}$$

The control input for the ACC controller of the follower car utilizing the CS strategy is described as:

$$u_i = \kappa_a \delta_i + \kappa_b \cdot \int_0^t \delta_i d\tau + \kappa_c \frac{d\delta_i}{dt} \tag{15}$$

where all the control gains $\kappa_a, \kappa_b, \kappa_c$ are designed for the PID controller, respectively.

If we considered that the vehicle's acceleration is controlled instantaneously $\ddot{s}_i = u_i$, and substituting into equation ((15)) leads to:

$$\dddot{s}_i = \kappa_a \delta_i + \kappa_b \dot{\delta}_i + \kappa_c \ddot{\delta}_i \tag{16}$$

yields:

$$\dddot{\delta}_i = \kappa_b \delta_{i-1} + \kappa_a \dot{\delta}_i i - 1 + \kappa_c \ddot{\delta}_{i-1} - \kappa_b \delta_i - \kappa_a \dot{\delta}_i - \kappa_c \ddot{\delta}_i \tag{17}$$

We can be written the following closed-loop error dynamics as follows:

$$\dddot{\delta}_i + \kappa_b \delta_i + \kappa_a \dot{\delta}_i + \kappa_c \ddot{\delta}_i = \kappa_b \delta_{i-1} + \kappa_a \dot{\delta}_i i - 1 + \kappa_c \ddot{\delta}_{i-1} \tag{18}$$

Using the Laplace transform for equation (18), The transfer function of the closed-loop system for spacing error between two successive cars pairs, $\delta_i(s) = H_i(s)\delta_{i-1}(s)$, is given by:

$$\mathbf{H_i(s)} = \frac{\kappa_c s^2 + \kappa_a s + \kappa_b}{s^3 + \kappa_c s^2 + \kappa_a s + \kappa_b}, \qquad i = \overline{1,N} \tag{19}$$

### 4.2 ACC System Design base on the Constant Time Headway Strategy

Using the CTH strategy is getting increasingly popular in a platoon, which is one of the spacing policies used most commonly and it has been discussed in references Luu et al. (2019b), Luu et al. (2020a), Rajamani (2011).

In the CTH strategy, the desired inter-car distance is not constant and it is proportional to speed of car:

$$\widetilde{\xi}_{i,ref}(t) = c_0 + \tau_h \widetilde{v}_i(t) \tag{20}$$

where $c_0$, $\tau_h$, $\widetilde{v}_i$ are denoted respectively the desired static distance of cars, i.e the required distance at zero velocity, the time headway utilized by the car $i$, the actual velocity of the car $i$ , respectively. $l_{i-1}$ is the car length.

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

$$\widetilde{\xi}_i(t) = \widetilde{s}_{i-1}(t) - [\widetilde{s}_i(t) + l_{i-1}] \tag{21}$$

The spacing errors for the closed-loop system between between two consecutive pairs is defined in Luu et al. (2019a), Luu et al. (2020a):

$$\widetilde{\delta}_i(t) = \widetilde{\xi}_i(t) - \widetilde{\xi}_{i,ref}(t) = \widetilde{s}_{i-1}(t) - \widetilde{s}_i(t) - l_{i-1} - c_0 - \tau_h \widetilde{v}_i(t) \tag{22}$$

In the platoon, length from the leader car to the last car consisting of the length cars and distances between cars is described as:

$$\widetilde{L}_{platoon}(t) = \widetilde{s}_0(t) - \widetilde{s}_N(t) \tag{23}$$

Consider the following simple CTH strategy controller Luu et al. (2019a), Rajamani (2011), Darbha et al. (2019), that is utilized in ACC system:

$$\widetilde{u}_i = \kappa_v(\widetilde{v}_{i-1} - \widetilde{v}_i) + \kappa_s(\widetilde{s}_{i-1} - \widetilde{s}_i - l_{i-1} - c_0 - \tau_h \widetilde{v}_i) \tag{24}$$

where $\kappa_v, \kappa_s$ are respectively the parameters of the algorithm. Notice that this system is only employed the information from measuring devices mounted on the cars, i.e. V2V information equipment is not installed on all cars as is indicated in Fig.1.

Utilizing the mathematical modeling equation (6) with the controller equation (24), we are obtained:

$$\varsigma_i \dddot{\widetilde{\delta}}_i + \ddot{\widetilde{\delta}}_i + (\kappa_v + \kappa_s \tau_h)\dot{\widetilde{\delta}}_i + \kappa_s \widetilde{\delta}_i = \kappa_v \dot{\widetilde{\delta}}_{i-1} + \kappa_s \widetilde{\delta}_{i-1} \tag{25}$$

Using the Laplace transform for equation (25), The transfer function of the closed-loop system for spacing error between two consecutive cars pairs, $\widetilde{\delta}_i(s) = \widetilde{H}_i(s)\widetilde{\delta}_{i-1}(s)$, is given by:

$$\widetilde{\mathbf{H}}_\mathbf{i}(\mathbf{s}) = \frac{\kappa_v s + \kappa_s}{\varsigma_i s^3 + s^2 + (\kappa_v + \kappa_s \tau_h)s + \kappa_s}, \qquad i = \overline{1,N} \tag{26}$$

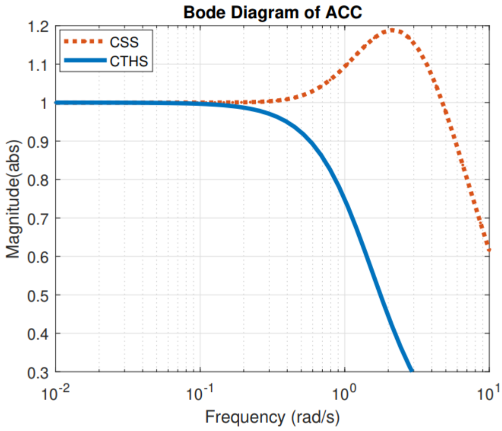


Fig. 5. Frequency response of transfer function for spacing policies: CS strategy and CTH strategy

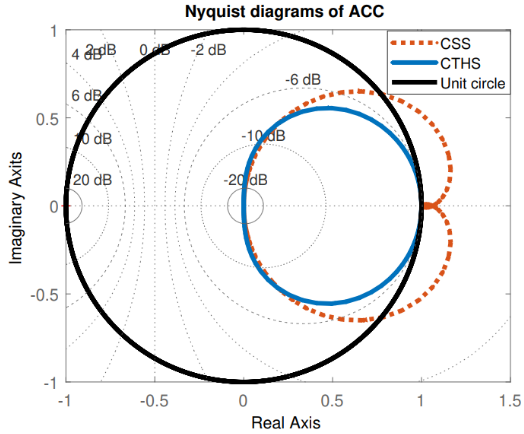


Fig. 6. Nyquist diagrams of transfer function for spacing policies: CS strategy and CTH strategy

### *4.3 Stability Analysis for the ACC System*

Individual vehicle stability is generally depicted vehicles converging to given trajectories Dolk et al. (2017), Swaroop and Hedrick (1999), Ghasemi et al. (2013). However, only each individual stable vehicle could amplify a small disturbance and cause a collision between vehicles in a platoon.

To solve this problem, string stability has been discussed and studied extensively. Intuitively, the platoon is called to be string stable when the amplitude of distance error between consecutive cars decreases along the string as propagating towards the tail of the string, the platoon is string stable Peppard (1974), Feng et al. (2019), Monteil et al. (2019). In other words, string instability is small disturbances acting on one car can cause large errors in the distance between two successive cars pairs even make them amplify along car string Guo and Yue (2011). According to the definition about string stability which has been proposed for ADASs, can be found in Swaroop and Hedrick (1996), Ploeg et al. (2013), i.e. the magnitude of the error in the frequency domain between two successive cars pairs:

$$||\mathbf{H_i}(\mathbf{j}\omega)||_\infty \leq 1 \quad (27)$$

$$||\widetilde{\mathbf{H}}_\mathbf{i}(\mathbf{j}\omega)||_\infty \leq 1 \quad (28)$$

For the CTH strategy, using the control law from equation (24), string stable if and only if $\tau_h \geq 2\varsigma_0$ as in Rajamani (2011), Swaroop and Rajagopal (2001).

Next, Bode and Nyquist diagrams as in Figs.5, 6 are used to evaluate the stability of a platoon of car/truck through string stability conditions equations (27), (28). In Figs.5, 6 indicates transfer functions of the distance errors between adjacent cars is based on the CS, CTH strategies.

The CTH strategy indicates that the platoon of cars is string stable, as the corresponding Nyquist diagrams is inside the unit circle with a corresponding radius of 1. Besides, the maximum magnitude is less than or equal 1.

In contrast, the CS strategy indicates that the platoon of cars becomes string unstable, as Nyquist diagram is clearly outside the unit circle, and the maximum magnitude is greater than 1 as in the Bode diagram.

## 5. CAR STRUCTURE DESCRIPTION IN ROBOT PLATOONING

In real time application in the car control area, new prototype smart car is made and perform the experiment as a approach techniques of longitudinal control for autonomous vehicle, the highlight of the smart car prototype is its simplicity and real-time applicability.

The smart car prototype as ”Arduino cars” is made with the support of the PRECIS Research Center, Laboratory 10 - Advanced Control Systems for Real - Time Applications at our faculty. It is equipped with various sensors, each device is tested in real time separately, for details tested several sensors illustrated in Figs.7, 8. Then they are integrated together to obtain new prototype. The code will be written by C++ language,... with ARDUINO interface board. Additionally, in comparison with other available nowadays prototype utilized in car control area, this proposed prototype are implemented at low-cost (for details see table 1), and the devices is available on the market and easily buy it, these is an outstanding advantage.

The smart car for robot platooning is described in the laboratory world as in Fig.9 considers one leader and three followers. The position of this smart car relative to the demarcation line(s) of the road lane (for details see in Fig.9) is determined by left - right infrared sensor lines. These sensor lines assist new prototype to determine the left and right of road markings and keep the middle of the lane. The sensing device transmits the signal to the micro-controller to control the electric motor, that give speed input (PWM) almost instantaneous and accurate to achive control goal. Structurally, this electric car has no complex vehicle dynamics, it is static in the laboratory, there is no significant airflow around the car, and input devices, output devices, and structure of the model car is introduced and discussed in Luu and Lupu (2019), Luu et al. (2019a).

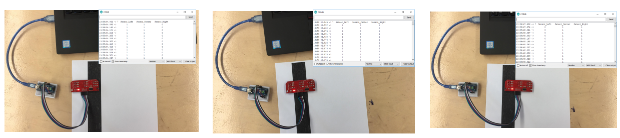

Fig. 7. Testing lines sensor

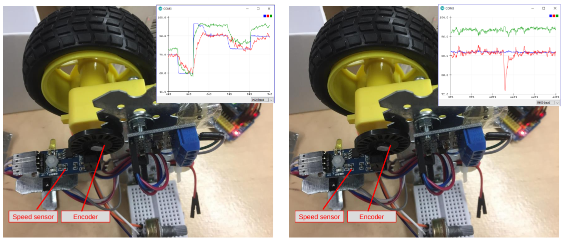


Fig. 8. Testing infrared speed sensor

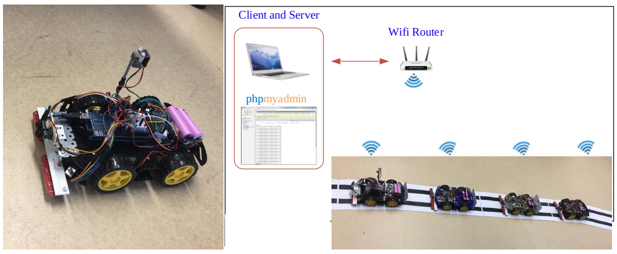


Fig. 9. Experiments with platoons of smart cars in the laboratory

Table 1. Components of each smart car

| Component | Qty | Unit price **(USD)** | Total price **(USD)** |
|---|---|---|---|
| Smart car model | 1 | 20 | 20 |
| Arduino MEGA 2560 | 1 | 9.0 | 9.0 |
| L9110S Driver of the Motor | 2 | 2.0 | 4.0 |
| Spacing Sensor | 1 | 7.2 | 7.2 |
| Lines Sensor | 2 | 7.5 | 15.0 |
| Speed Sensor | 4 | 2.0 | 8.0 |
| Triaxial accelerometer sensor | 1 | 5.0 | 5.0 |
| WeMos D1 Mini ESP8266 | 1 | 7.0 | 7.0 |
| Battery | 2 | 7.5 | 15.0 |
| Micro SD card | 1 | 3.0 | 3.0 |
| Cable and other | 1 | 3.0 | 3.0 |
| | | **Total** | **96.2** |

## 6. SIMULATION AND EXPERIMENTS RESULTS

In order to indicate how to apply the platoon of cars with different controller, first in a numerical example established in Matlab/Simulink to evaluated the effectiveness of the proposed approach for car platoons, and compare the performance of the platoon equiped with the ACC system under different spacing strategies, including the CTH strategy and the CS strategy. Finally, a platoon of smart cars based on the CS strategy will test in the laboratory world.

### *6.1 Simulation Results*

A comparative studies are conducted to illustrate the vehicle platooning by using the ACC system to improve arterial intersection operations. The intersection platoon wait at a red light signal which enables thus to start moving in a coordinated manner once the signal light turns green with simulation scenarios for two strategies, respectively. Specifically, all 21 cars (a leader, $i = 0$ and 20 followers with $i = \overline{1,21}$) are connected in the intersection, as in Fig.1), while they are waiting for the green light situation, is considered, and the green phase and yellow phase is equal to 30s.

For the leader car, the *PD* controller's design is done with the PID tuner tool in MATLAB, resulting the tuning parameters $K_p = 75.25, K_d = 105.5$.

Set the engine time lag to $\varsigma_i = 0.15s$. The initial positions and velocities of the cars are respectively set as $s_i(0) = [0,13,26,39,52,65,78,91,104,117,130,143,156,169,182,195,208,221,234,247,260]^T m$, $v_i(0) = 0m/s$, $d_s = 5m$, and $l_i = 5m$.

In the CS strategy, the goal is to keep a reference fixed spacing irrespective between members. The desired distance between two successive cars pairs is set as $\xi_{i,ref}(t) = 8m$, with zero initial tracking errors. The basic parameters of the controller are used: $\kappa_a = 11.26; \kappa_b = 4.64; \kappa_c = 6.82;$

In the CTH strategy, the desired spacing of a controlled car changes with its velocity. The gain parameters of this controller are obtained: $c_0 = 2m; \tau_h = 0.95s; \kappa_v = 0.8; \kappa_s = 2;$

At time 0s, the traffic signal light at the intersection is red and all 21 cars are waiting at the queue. At time 30s, the signal turns into green light and all cars gradually leave the intersection with the profiles of the car's velocity is given as follow:

$$v_{ref} = \begin{cases} 0m/s, & 0 \leq t \leq 30s \\ 0.8t - 24m/s, & 30 < t \leq 45s \\ 12m/s, & 45 \leq t \leq 85s \end{cases} \tag{29}$$

The driving behavior of cars in platoon are show in Fig.10. The leader car maintains the desired reference velocity. The followers regulate the same velocity as the leader car while staying the desired distance defined based on the CS, CTH strategies.

Fig.10 indicates that all 21 cars can succeed to pass through signalized intersection, when the entire cars must move at least 265m, i.e, $L_{platoon} + d_s = 265m$. With such a scenario, we show that the case of the platoon of cars with the CS strategy increase traffic throughput more than the platoon of cars with the CTH strategy. The ACC system based on the CS strategy can effectively improve urban arterial capacity. This aspect can be better explained by using Figs.10a1, 10a2. As seen, all 21 cars succeeded to pass the intersection through the CS strategy due to the smaller distance between the cars, while only 11 cars (0 to the $10^{th}$ cars) passed the intersection, having the last 10 cars ($11^{th}$ to the $21^{th}$ cars) of the ACC system based on the CTH strategy did not pass the intersection. At time 60s, the signal light turns red, the $11^{th}$ car can not pass the the intersection at the position of 265m, the $11^{th}$ car must brake and stop at there to lead the cars behind it to stop at the corresponding position at time 60s.

Figs.10b1, 10b2 show velocity profiles of the platoon of cars for the CS, CTH strategies, respectively. The velocity of cars with the CTH strategy illustrates only 11 cars that have passed the intersection. Clearly, the platoon of cars have reached consensus with respect to velocity.

The comparison between Figs.10c1, 10c2 indicates that the deviation of distance of cars based on the CTH strategy is smaller. The deviation of maximum distance of cars with CTH strategy is 0.28m, while that of with CS strategy is 0.5m. We notice that the distance error of cars for both cases converges to zero-value, i.e. each car is stable individually.

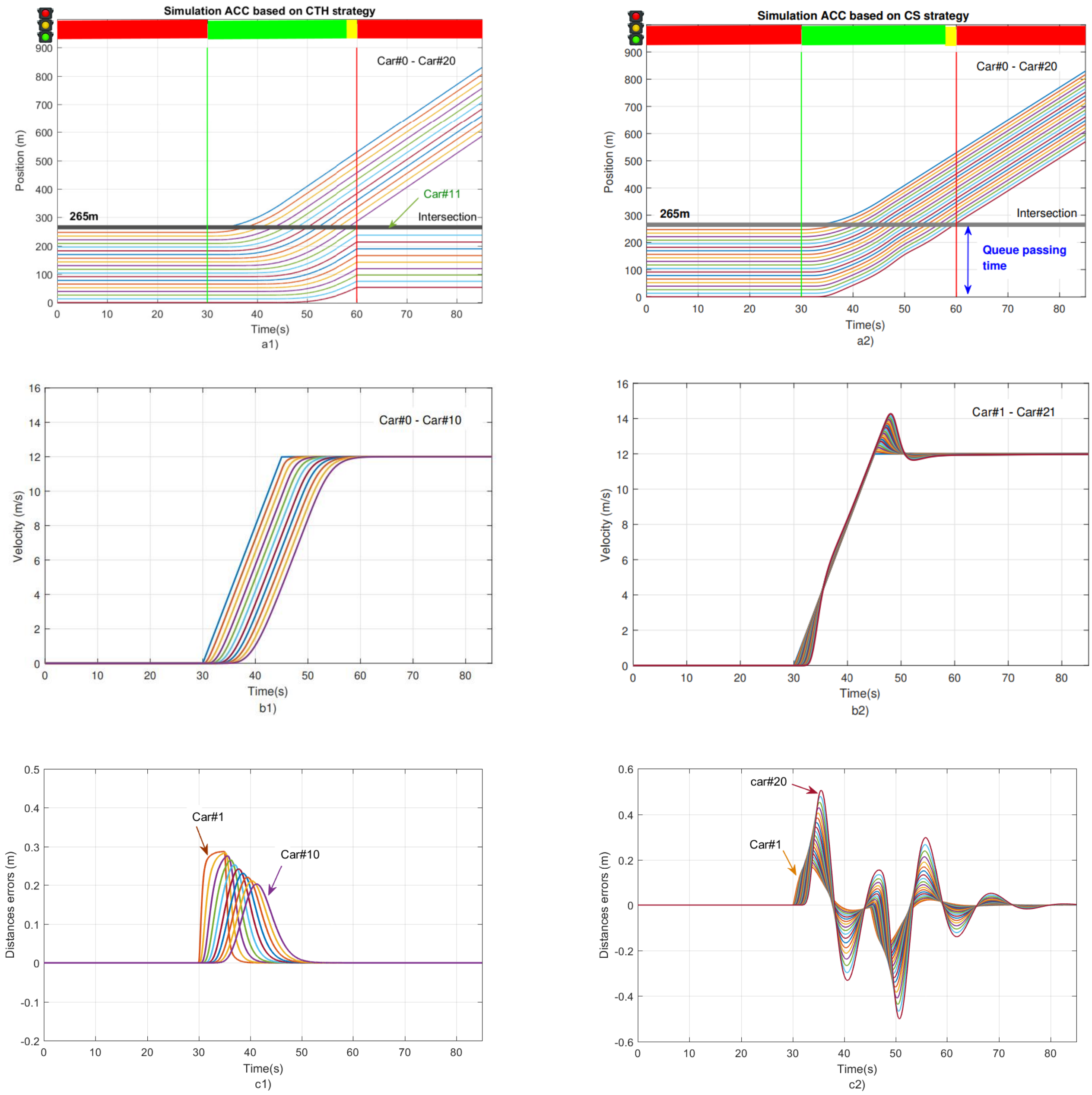


Fig. 10. The results of a platoon of cars: (a1-c1) CTH strategy; (a2-c2) CS strategy

It is seen from Fig.10c1 that the distance errors of all cars based on the CTH strategy can achieve string stability, i.e. $|\widetilde{\delta}_1| \geq |\widetilde{\delta}_2| \geq ... \geq |\widetilde{\delta}_{10}| \geq |\widetilde{\delta}_{11}|$. In other words, string stability ensures that the amplitude of the distance error between consecutive cars will decrease as they propagate along the car stream. This confirm the correctness of string stability conditions in Subsection 4.3.

Unlike as in Fig.10c1, we show that the distance errors based on the CS strategy do not decrease as they propagate along the car stream in Fig.10d2, i.e. $|\delta_1| \leq |\delta_2| \leq ... \leq |\delta_{20}| \leq |\delta_{21}|$, and hence their result may not ensure string stable.

To sum up, the effectiveness of the proposed approach is well demonstrated, i.e. the platoon equipped the ACC system with CTH strategy has better string stable, while the platoon equipped the ACC system with CS strategy ensures increasing throughput, they improve the overall traffic flows and individual driving efficiency on urban roads which is evaluated in typical urban traffic at the signalized intersection, but the platoon of cars is string unstable.

### *6.2 Experiments Results with the Smart Cars*

In what follows, the proposed approach is tested for four smart cars called Arduino cars travelling single lane (line marked) on the floor in the laboratory world as in Fig.9 to verify the effectiveness of the practical use.

The smart car for the robot platooning is described as in sector 5, consisting of one leader and three followers. Robot platooning is travelled with the distance which is actually very small, so using the infrared sensor is measured the distance between two successive cars pairs. The longitudinal velocity is measured from encoder sensor mounted on the rear wheels.

We will focus for followers equipped with ACC system based on CS strategy which is a common type of strategy that shows real-time applicability.

The leader smart car stays the speed at 30cm/s in during time interval [2s, 25s], and then decelerates from 30cm/s to 20 cm/s during time interval [25s, 31s], and then stays the speed at 20cm/s during time interval [31s, 50s], where the initial distance and the fixed distance in the platoon is set to 25cm.

Their velocities, the distances, and errors distance between the smart cars are indicated in Figures 11 -13, respectively. From these figures, we observe that velocity tracking operates well.

Clearly, the distance of each smart car in a robot platooning converges to the desired value. Furthermore, the distance error of each smart car converges to zero-value, i.e, all smart car is stable individually. The smart car exist a little large distance at the start (time at 2s) and a little big overshoot later, caused by a higher starting voltage than the minimum operating voltage.

The distance errors of each smart car increase as they propagate along the car stream, and hence their result maybe not guarantee string stable.

It is clearly seen from the simulation and testing results that the testing results satisfied with the request for the theory and experimental. However: **(1)**: The time delay has existed when the Mega Arduino of the smart car computes the control command for the electric motors; **(2)**: The hardware is affected by a manifold of disturbance, noise or environment brightness which leads to the unstable measurement of the spacing. But, does not seriously affect the results. Overall, an accurate sensor is better at will improve the performance of the controller in a platooning.

## 7. CONCLUSIONS

In this study, numerical simulations are implemented by software Matlab/Simulink for the platoon using the ACC system under different spacing strategies to demonstrate the differences, advantages, and disadvantages of each spacing strategy through evaluating in typical urban traffic at the signalized intersection.

The obtained results show that each car in a platoon for both two spacing strategies is stable individually, but the platoon with CTH strategy has better string stable performance. In contrast, the ACC system with the CS strategy could allow more cars to pass through the intersection on a green cycle than the ACC system with the CTH strategy, due to the smaller distance between the cars and thus improving the efficiency of intersections and reducting urban congestion. In fact, we need to balance between stability, safety and traffic capacity, so the distances strategies for a platoon is chosen based on design purposes of the system.

Arduino cars in a robot platooning equipped with the ACC system are tested base on the CS strategy and each smart car obtain only the distance between itself and the smart car in front of it via range-limited sensors. Components to make the prototype car is low-cost and is available on the market (introduced in Luu et al. (2019a)), easy to implement in real-time. Testing results confirm the practicability and effectiveness of the proposed method. Next step in future, the smart cars platooning will test and integrate cooperative platoon of cars solution base on the CTH strategy.

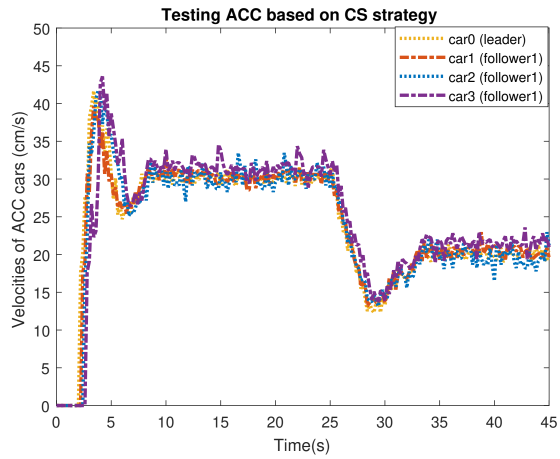


Fig. 11. The velocities of ACC robots platooning with CS strategy

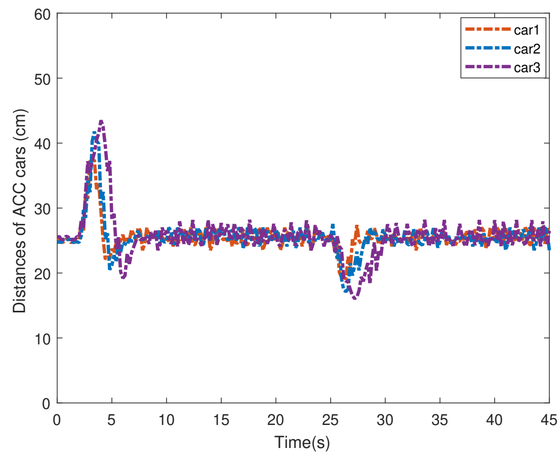


Fig. 12. The distances of ACC robots in the platoon with CS strategy

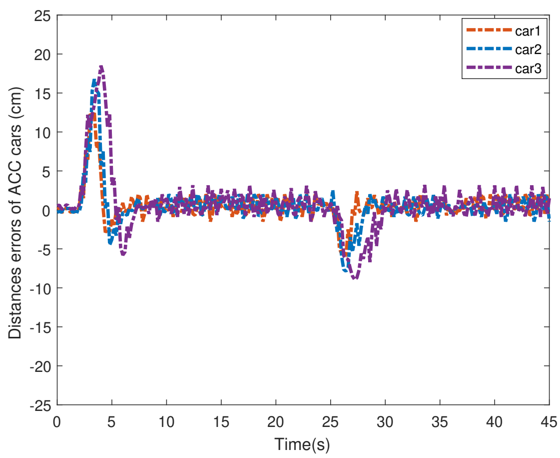


Fig. 13. The distance errors of ACC robots in the platoon with CS strategy

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