# Performance Comparison of Automated Vehicle Controllers

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**Abstract**: The design of intelligent vehicle control system is an important part of AHS (Automated highway systems) . This paper addresses the problem of longitudinal control of a vehicles platoon and presents the comparison of several control algorithms of vehicle longitudinal control system. Simulation of the appropriate platoon performance is presented.

Keywords: AHS, longitudinal control, platoon stability, vehicles.
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## 1 Introduction

Automated highway systems (AHS) have drawn more and more attention in recent years because full automation can greatly increase highway capacity while improving safety. In each platoon of AHS, every vehicle (except the leading car) tightly follows the preceding vehicle, and can react quickly to the preceding car and emergency.

The design of intelligent vehicle control system is an important part of AHS, and it involves automatic control of throttle and brake [1] . One of the objectives of intelligent vehicle control is to achieve automatic vehicle following in the longitudinal direction by following the speed response of the leading vehicle and keep a safe inter-vehicle spacing.

In this paper, we discuss and compare the performance of several vehicle longitudinal controllers. The paper is organized as follows: In section 2 safety distance policy and control objective of longitudinal control are discussed. Several approaches of longitudinal control are given in section 3. In section 4, simulation results are presented and performance of the controllers are discussed. Finally, some conclusion remarks are given in section 5.

## 2 Longitudinal Control

### 2.1 Safety Distance Policy

To obtain higher traffic throughput, platoons must operate with small inter-vehicle spacing and many vehicles in each group. However, for safe vehicle following, each vehicle is required to keep a safe distance from its preceding vehicle. The required safety distance should consider the vehicle´s performance and braking capabilities, rider's comfort constraints, road conditions, senor/actuator errors, etc. The fact that platoon stability cannot be achieved for platoons with constant inter-vehicle spacing if there is no communication of inter-vehicle information and platoon stability can be guaranteed if the information (such as velocity, acceleration, position, etc.) of the leading vehicle is transmitted to the other vehicles in the platoon. But if we adopt the constant time headway policy that the desired inter-vehicle distance depends on the velocity of the controlled vehicle, platoon stability may be obtained without information exchange among vehicles.

The expression for the desired inter-vehicle separation is:

$$S_d=S_0+hv_i \tag{1}$$

In the above equation, $S_d$ is the desired separation between vehicles, the parameter $h$ is called time headway, and $v_i$ is the velocity of the ith controlled vehicle. If $h$ is zero, this is the case of constant spacing policy. And if $h$ is a positive constant, this is the constant time headway policy. If we take the constant time headway policy, although it is much easier to obtain platoon stability, the price of larger spacing between adjacent vehicles must be paid.

In order to maintain the platoon stability but without increasing inter-vehicle spacing under autonomous vehicle operation, Yanakiev et al. [2-3] proposed variable time headway instead of the time headway being fixed, the headway varies with the relative speed $v_r$ between adjacent vehicles as

$$h=h_0-c_h v_r \tag{2}$$

where $h_0$, $c_h$ are both positive constant. We can see that, if $v_r>0$ , i.e., the preceding car is faster than the controlled car, then it is safer to reduce the headway, i.e., decrease the desired inter-vehicle separation; and if $v_r<0$, i.e.,

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the preceding car is slower than the controlled car, then it is required to increase the headway. The variable headway results in the smoother control activity and smaller spacing than the constant headway in the steady state.

### 2.2 Control Objective

The spacing deviation of the ith vehicle from the desired safety distance is defined as follows:

$$\delta_i = x_{i-1} - x_i - l_i - S_{di} \tag{3}$$

The relative velocity is defined as follows:

$$v_{ri} = v_{i-1} - v_i \tag{4}$$

where, $x_i$ ($v_i$), $x_{i-1}$ ($v_{i-1}$) is the position (velocity) of the ith vehicle and $(i-1)$ st (controlled) vehicle as shown in Fig.1, $l_i$ is the length of the controlled vehicle.

The control objective is to regulate $\delta_i$ and $v_{ri}$ to zero, i.e., $\lim_{t\to\infty}\delta_i(t)=0$, and $\lim_{t\to\infty}v_{ri}(t)=0$ .

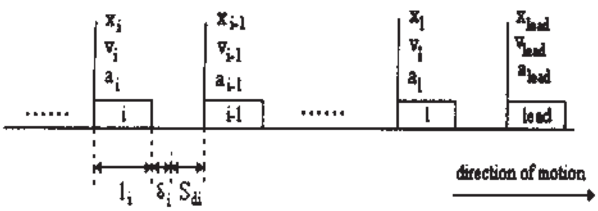


Fig. 1 Platoon configuration

The tasks of regulating the relative velocity and the spacing deviation can be combined into the control objective $v_{ri}+k\delta_i=0$ , where $k$ is a positive design constant. This control objective makes sense intuitively: if two vehicles are closer than desired ($\delta_i<0$) and the control objective is satisfied ($v_{ri}=-\delta_i>0$), then the following car is moving slower than the preceding car, which is what we expect. And the situation is also what we want if $\delta_i>0$. For constant $h$ and $k$, it has been proved that, when the leading vehicle's velocity is steady and the above control objective is achieved ($v_{ri}+k\delta_i\equiv0$), both the relative velocity and the separation error are regulated: $v_{ri}\to0$ and $\delta_i\to0$.

As we mentioned before, except the performance of individual vehicle, platoon stability should also be guaranteed. Otherwise, a small change of spacing, velocity or acceleration of the leading vehicle will result in large oscillation of the followers, which is unacceptable.

Therefore, in addition to regulate $\delta_i$ and $v_{ri}$ to zero, platoon stability is also required, all of these three makes up of the control objective of longitudinal control.

## 3 Control Algorithms

### 3.1 Vehicle Model

For longitudinal control, the vehicle dynamic model may be considered simply as a one-input (positive value for throttle angle command and negative value for torque command, or control effort, engine input) one-output (vehicle speed) system. The system may be also considered as a two-input (throttle angle command and brake torque command) one-output system, and we can separate this system into a throttle angle to speed and braking torque to speed subsystems, due to the throttle and brake controllers are not allowed to act simultaneously. A lot of vehicle models for longitudinal control are proposed. One of the simplest models is [4] :

$$\ddot{x}_i = (u_i - c_i\dot{x}_i^2 - f_i)\ /M_i \tag{5}$$

where $x_i$, $u_i$, $c_i$, $f_i$, $M_i$ are the position, control effort, effective aerodynamic drag coefficient, rolling resistance friction, and effective inertia of the ith following vehicle, respectively.

If we consider the engine dynamics, the control effort $u_i$ can be model as a first order system:

$$\dot{u}_i = (-u_i + u_{ic})/\tau_i \tag{6}$$

where, $u_{ic}$ is the control effort when we consider the actuator dynamics.

### 3.2 Control Laws

Most of the longitudinal control system consists of an upper level controller and a lower level controller. The upper level controller determines the desired or "synthetic" acceleration for each car in the platoon. The lower level controller determines the throttle and/or brake command required to track the desired acceleration.

Taking the vehicle model of previous section and design the desired vehicle acceleration (or synthetic input)$a_i^c=f(x_{i-1}$, $v_{i-1}$, $a_{i-1}$, $x_i$, $v_i$, $a_i$, $v_L$, $a_L)$, we can substitute this into the vehicle model and get the control effort as:$u_i=M_i a_i^c+c_i v_i^2+f_i$.

However, if there are parameter uncertainties, such as mass of vehicle, aerodynamic drag, and tire drag, we may choose the adaptive law of parameter. And if there are un-modeled dynamics and unknown disturbances, we may design robust control law. But the robust adaptive longitudinal controllers for the parameter uncertainty and disturbance are not considered in this paper.

In this paper, we mainly consider and discuss the different performance of several longitudinal vehicle controllers and we think that we have got the vehicle model clearly, so, we only emphasize the different approaches to obtain the expected acceleration (or the derivative of the expected acceleration) based on $\delta_i$ , $v_{ri}$ , the state (such as velocity, acceleration, etc.) of the car, and don't care much about the detailed vehicle models and parameter uncertainties.

### A. PD controller

The idea of PD controller comes from the decision making of human driver. The human driver senses the distance between his car and the front car, and also estimates the possible change of the distance based on the velocity of his car and the front car, then he controls the acceleration of his car to maintain the safety spacing. The control law is:

$$a_i^c = c_s\delta_i + c_v\dot{\delta}_i \tag{7a}$$

$$u_i = \varphi(a_i^c, \dot{x}_i) \tag{7b}$$

where, $c_s$ and $c_v$ are the parameters of proportion term and differential term, respectively. And φ is a function of the vehicle model in which the output variable is control effort, for example, for the vehicle model of equation (5),

$$\varphi(y_1, y_2) = M_i y_1 + c_i y_2^2 + f_i$$

The PD controller is very simple, however, the performance of the PD controller is very limited. It can be used for constant time headway safety policy only. For constant spacing policy, this method cannot guarantee platoon stability.

### B. Controller proposed by Ioannou [1]

This controller is not cooperative (it doesn't exchange information with other vehicles of the platoon) either as PD controller, and considers the velocity and acceleration of the controlled vehicle. By adopting constant time headway policy, the performance of the controller is good if the parameters of the controller are chosen appropriately. It can not only eliminate the slinky effects, but also achieve a faster and better transient response. Ioannou's controller considers the actuator dynamics of vehicle model, so it adopts the vehicle model as:

$$\frac{d}{dt}\ddot{x}_i(t) = b(\dot{x}_i, \ddot{x}_i) + \alpha(\dot{x}_i)u_i(t) \tag{8}$$

So, this controller obtains the desired derivative of the expected acceleration of the controlled car based on the velocity and acceleration of the controlled car besides the spacing deviation and the derivative of spacing deviation in the PD controller. The control law is [5]:

$$c_i(t) = \dot{a}_i^c = C_p\delta_i(t) + C_v\dot{\delta}_i(t) + K_v v_i(t) + K_a a_i(t) \tag{9}$$

$$u_i(t) = [c_i(t) - b(\dot{x}_i, \ddot{x}_i)]/\alpha(\dot{x}_i) \tag{10}$$

The platoon dynamics can be obtained based on the relationship between $\delta_{i-1}(t)$ and $\delta_i(t)$. Then the constants $C_p$, $C_v, K_v, K_a$ are to be chosen to meet the design considerations such as stability of individual vehicles, $\lim_{t\to\infty}\delta_i(t)=0$ and platoon stability. But this controller cannot be used in constant spacing policy, because as we mentioned before, the platoon stability cannot be guaranteed without information exchange among vehicles.

### C. Controller with two-side information

This controller uses the information of the preceding vehicle as well as the information of the following vehicle [6]. Because the controller also uses the follower's information to avoid rear-end collision, it is expected that this controller could achieve better performance than the controller using only the information of the predecessor. The control law of equation (7a) becomes,

$$a_i^c = k_{i1}[\delta_i + q(v_{i-1} - v_i)] - k_{i2}[\delta_{i+1} + q(v_i - v_{i-1})]$$

where, $k_{i1}$, $k_{i2}$, $q>0$ are design constants.

This control law makes sense intuitively from the control objective $v_{ri}+k\delta_i=0$ : if $v_{ri}+k\delta_i>0$ of the preceding vehicle or $v_{r(i+1)}+k\delta_{i+1}<0$ of the following vehicle, then the controlled vehicle make an acceleration; if $v_{ri}+k\delta_i<0$ of the preceding vehicle or $v_{r(i+1)}+k\delta_{i+1}>0$ of the following vehicle, then the controlled vehicle make a deceleration.

It has been proven that the platoon stability can be guaranteed only if [4]

$$k_{i1} \geqq k_{i2}/4 > 0, \ \forall i \tag{12}$$

The above theorem is tenable not only for constant time headway policy, but also for constant spacing policy. But this method causes much larger spacing deviation and the acceleration is more fluctuant than the other methods.

### D. Dynamic surface controller

Hedrick, Swaroop et al. [7] design the longitudinal controller using "Multiple Sliding Surface" methodology, which is closely related to the sliding mode control.

A sliding surface that leads to accurate spacing control and overall platoon stability is:

$$S_i = \dot{\delta}_i + q_1\delta_i + q_3(\dot{x}_i - \dot{x}_0) + q_4\left(x_i - x_0 - \sum_{j=1}^{i} L_j\right) \tag{13}$$

where, $q_1$, $q_3$ and $q_4$ are control parameters, $x_0$ and $\dot{x}_0$ are the position and velocity of the leading vehicle (i.e. the first vehicle of the platoon), respectively. $L_j$ is the desired inter-vehicle distance of the ith vehicle and its predecessor, i.e.,

$$L_j = l_j + S_{dj} \tag{14}$$

Here, $l_j$ is the length of jth vehicle, and $S_{dj}$ is the desired inter-vehicle separation, which have mentioned before.

To make $\delta_i$ converge to zero, we want

$$\dot{S}_i = -\lambda_i S_i \tag{15}$$

We can obtain the desired vehicle acceleration (or synthetic input) by solving the above equations and get the control effort afterwards.

$$a_i^c = \frac{\ddot{x}_{i-1} - q_1\dot{\varepsilon}_i + q_3\ddot{x}_{l0} - q_4(\dot{x}_i - \dot{x}_0) - \lambda_i S_i}{1+q_3} \tag{16}$$

The above dynamic surface controller can guarantee the platoon stability as well as individual vehicle stability not only for constant time headway policy, but also for constant spacing policy. However, it needs the state of the leading vehicle, i.e., it requires communication with the leading vehicle.

**E. Controller with variable time headway and error gain**

The controller proposed by Ioannou et al [1] can also guarantee the platoon stability without communication with other vehicles, but keep larger inter-vehicle distance because of constant time headway policy. The Dynamic surface controller can guarantee the platoon stability, and also keep smaller inter-vehicle distance because it can adopt constant spacing policy. But the price it paid is the communication with the leading vehicle. Is it possible to keep platoon stability and smaller inter-vehicle distance under autonomous operation (i.e., depend only on information obtained by the sensors located on the vehicle itself)? Yanakiev et al. [2-3] have tried to solve this problem by adopting the nonlinear modification of the control objective ($v_{ri}+k\delta_i=0$) propose in section 2.2, i.e., variable time headway $h$ (proposed in section 2.1) and variable separation error gain $k$ of the control objective. The modification of $k$ is as follows:

$$k = c_k + (k_0 - c_k)e^{-\sigma\delta^2} \quad (17)$$

where, $0<c_k<k_0$ and $\sigma \geqslant 0$ are design constants.

We can explain the above modification as follows. Because the control objective is $v_{ri}+k\delta_i=0$, the following vehicle will react aggressively with $k$ constant when it falls far behind the preceding vehicle ($\delta_i$ is large positive number and $v_{ri}=-k\delta_i$, so $v_{ri}$ will be large). We should avoid this maneuver in order not to make collision and un-smooth happen. So, we should let $k$ smaller when $\delta_i$ is positively larger. The following vehicle will decelerate aggressively with $k$ constant when the preceding vehicle brakes ($\delta_i<0$). Because aggressive deceleration control actions are amplified upstream, the next vehicles of the platoon will reach the minimum acceleration permitted quickly. This maneuver will result in the collision between the vehicles of platoon's tail. Reducing the gain $k$ for negative $\delta$ makes the reaction of the first few vehicles less aggressive and allows the remaining vehicles to follow safely. If variable $h$ and $k$ are used, we can adopt the following PID controller based on the control objective $v_{ri}+k\delta_i=0$.

$$a_i^c = k_p(v_r + k\delta) + k_i \frac{1}{s}(v_r + k\delta) + k_d s(v_r + k\delta)$$

And we can also adopt the PIQ controller:

$$a_i^c = k_p(v_r + k\delta) + k_i(v_r + k\delta)/s + k_q(v_r + k\delta)\left|v_r + k\delta\right|$$

# 4 Simulation Results

The platoon performance of the controller is especially important when the leading cars accelerate or decelerate suddenly, such as the leading vehicle brakes suddenly to deal with the emergent situation. To compare the different performance of the different longitudinal controllers, simulations are performed for an eleven-vehicle platoon. In the simulation, we don't consider the uncertainties of vehicle models and the disturbance, and we don't take the time lag of sensors and actuators into account. So, we don't consider the robustness here.

We assume the leading vehicle accelerates form 0m/s to 24m/s within 40 seconds, and keep its velocity of 24m/s for 20 seconds, and decelerates from 24m/s to 14m/s at 60th second with acceleration of $-1m/s^2$. The whole simulation lasts 100 seconds. The spacing deviation, velocity, and acceleration of the following ten vehicles are illustrated for different longitudinal controllers from Fig.2 to Fig.6 (not all the simulation results are illustrated because of the limit of the paper). In all these figures, the dash-dot line, dotted line and solid line represent the first following vehicle (not the leading vehicle), fifth following vehicle, and tenth following vehicle, respectively.

The spacing deviation, velocity and acceleration response of PD controller with constant spacing policy are shown in Fig. 2. We can see from the figure that the slinky effect is very obvious when adopting constant spacing policy, so the PD controller can only used for constant time headway policy. And the performance of controller proposed by [1] with constant time headway policy and constant spacing policy are shown in Fig. 3. This controller cannot guarantee platoon stability either, however, the acceleration is smoother than that of the PD controller with constant time headway policy. The performance of controller with two-side information with constant time headway policy and constant spacing policy are shown in Fig. 4.

The controller with two-side information can guarantee platoon stability with constant spacing policy, however, the acceleration is more fluctuant. The performance of dynamic surface controller with constant spacing policy is shown in Fig. 5. The dynamic surface controller can guarantee platoon stability with constant spacing policy, and the spacing deviation, velocity and acceleration are better than any controllers, which we mentioned before. However, the controller needs communication with the leading vehicle to get the position, velocity and acceleration of the leading vehicle. The performance of controller with variable time headway and error gain is shown in Fig. 6.

# 5 Conclusions

This paper reviews and discusses the longitudinal control of

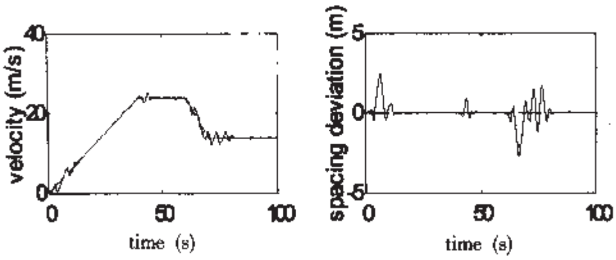

Fig. 2 Response of PD controller with constant spacing policy

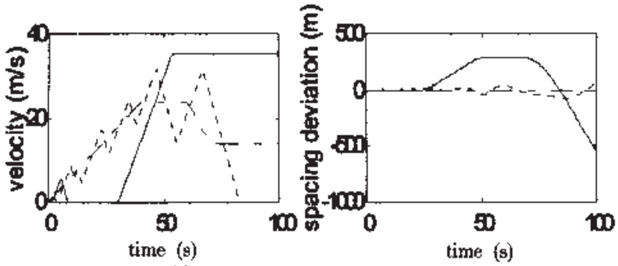

Fig. 3 Response of Ioannou's controller with constant time headway policy (above) and constant spacing policy (below)

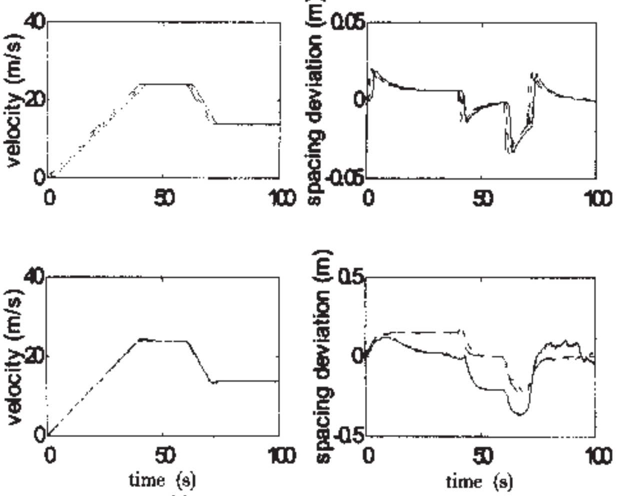

Fig. 4 Response of controller with two-side information with constant spacing policy

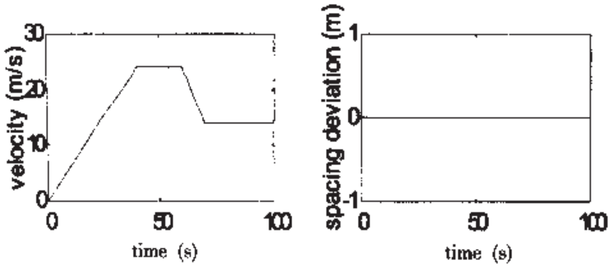

Fig. 5 Response of dynamic surface controller with constant spacing policy

AHS, and compares the performance of several longitudinal controllers from platoon performance. They are summarized as below,

**PD Controller**

Acceptable when adopting constant time headway policy, but the inter-vehicle distance is larger. There is slinky effect when adopting constant spacing policy.

**Controller proposed by Ioannou (93)**

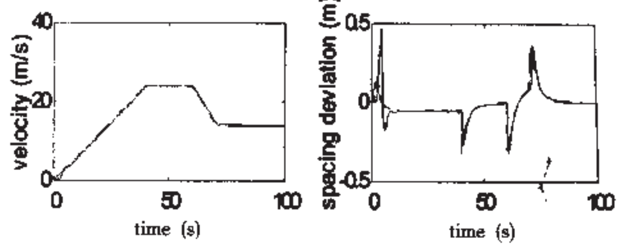

Fig. 6 Response of controller with variable time headway and error gain

Acceptable when adopting constant time headway policy, but the inter-vehicle distance is larger. Platoon stability can´t be achieved when adopting constant spacing policy.

**Controller with two-side information**

Platoon stability can be guaranteed for constant time headway and constant spacing policy. But the spacing deviation is larger.

**Dynamic surface controller**

Platoon stability can be guaranteed for constant spacing policy.

**Controller with variable $h$ and $k$**

Acceptable with smaller inter-vehicle separation.

From the perspective of platoon performance, the controller should guarantee the platoon stability and keep a small inter-vehicle distance to increase the highway capacity and safety.

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