Evaluation of Impacts of Adaptive Cruise Control on Mixed Traffic Flow

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Abstract

This paper addresses the impacts of Adaptive (Intelligent) Cruise Control (ACC) laws on the traffic flow. Semi-automated vehicles, such as ACC Vehicles, with the capability to automatically follow each other in the same lane, will coexist with manually driven vehicles on the existing roadway system before they become universal. This mixed fleet scenario creates new capacity and safety issues. In this paper, simulation results of various mixed fleet scenarios under different ACC laws are presented. Explicit comparison of two ACC laws, Constant Time Headway (CTH) and Variable Time Headway (VTH), are based on these results. It is found that the latter one has better performance in terms of capacity and stability of traffic. Throughput increases with the proportion of CTH vehicles when flow is below capacity conditions. But above capacity, speed variability increases and speed drops with the CTH traffic compared with manual traffic, while the VTH traffic always performs better.

Introduction

Ideally semi-automated vehicles, such as Adaptive (Intelligent) Cruise Control (ACC) Vehicles, with the capability to follow each other automatically in the same lane will improve traffic flow on existing roadways. Research on the properties of automated-vehicle platoons has shown the potential benefits for capacity and safety (Van Arem et al. 1996; Broqua et al. 1991; Minderhoud and Bovy 1998). It seems an appealing scenario that all of vehicles fall under the protection of advanced automation technologies. But, it is more reasonable to imagine that semi-automated vehicles will coexist with conventional manually driven vehicles at the initial stage of deployment. A mixed control scenario raises complex capacity and safety issues that we must probe before ACC becomes reality. Previous research estimated the impacts of ACC in some specific situations (Van Arem et al. 1996; Broqua et al. 1991; Minderhoud and Bovy 1998). Their results are meaningful for the traffic operators to outline the potential impacts of ACC. However, the traffic flow characteristics that ACC will bring are difficult to quantify. And it is not possible to make direct comparison among these documents, because these studies have employed different ACC algorithms, different driver behavior models and a different driving environment. Our research will begin with the simplified scheme they used. On the other hand, more complex situations are simulated in our microscopic traffic simulation program. We will try to summarize the impacts of ACC from a large number of simulations in which some stochastic mechanisms make the results more realistic.

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The second section discusses the methodology that can be used to evaluate the impacts of one ACC algorithm on traffic flow. The simulation program is also elaborated in this section. In the third section, a number of cases with mixed ACC and manually controlled traffic are simulated and analyzed using a microscopic traffic simulation program. We summarize the simulations on the different level of highway traffic as a function of the proportion of ACC vehicles. Different vehicle following scenarios with sudden increase and decease of traffic demand are analyzed in order to study the effect of the response of ACC vehicles in mixed traffic. The stability and transient response of traffic flow in different mixed traffic situations are illustrated in the results. Some concluding remarks in the fourth section complete the report.

Simulation of Mixed Traffic

Mixed Traffic Scenario

When traffic is comprised of vehicles controlled by different kinds of controllers, adaptive cruise control or/and human drivers, we consider it to be "mixed". For this simulation, Constant Time Headway (CTH) control and Variable Time Headway (VTH) control ACC algorithms were selected. A simple scenario of a one-lane highway section, 3.2 km long, with one entry and one exit was established. No lane changing is considered in this simulation work. Significant inter-vehicle interaction is present throughout the simulation. The scenarios were designed to test whether or not ACC could generate a higher capacity while guaranteeing more stable driving. Three typical scenarios are of most interest, these include:

(a) No-ACC traffic: All vehicles on the road are controlled by Gipps' car-following model (Gipps, 1981). This is the scenario to simulate the current manually controlled traffic.

(b) Mixed traffic: ACC vehicles mix with Gipps' vehicles with certain penetration. We'll highlight this scenario as the intermediary stage of ACC deployment. The characteristics of this scenario are expected to be more complicated than others.

(c) Pure ACC traffic: All vehicles are controlled by ACC.

The role of the driver of the ACC vehicle is the same in these scenarios. On reaching the target lane, the driver engages the automated control system of the vehicle that takes over the longitudinal control of the vehicle. The driver disengages the headway control of the ACC vehicle and accelerates to maximum speed if the highway is clear before him and at last exits the lane.

Dynamic Models Of The Components Of Mixed Traffic

(a) Vehicle Dynamics: The vehicle dynamics is simplified to a differential equation:

$$\dddot{x}_i = \frac{1}{\tau}(\ddot{x}_{ides} - \ddot{x}_i) \tag{1}$$

where: $\dddot{x}_i$ is the jerk of vehicle i; $\ddot{x}_i$ is the desired acceleration of vehicles i; $\ddot{x}_{ides}$ is the desired acceleration of vehicles i which is generated by the car-following model or ACC algorithm.

(b) Adaptive Cruise Control Policy

The most conventional ACC algorithm is **Constant Space Headway** control, which is in form of:

$$\begin{cases} \ddot{x}_{ides} = -k_1\varepsilon_i - k_2\dot{\varepsilon}_i \\ \varepsilon_i = x_i - x_{i-1} + L \end{cases} \tag{2}$$

It has been proven that this control law cannot guarantee string stability (Darbha and Rajagopal 1999). So we don not pursue this control law.

Constant Time Headway (CTH) control, which is in form of:

$$\begin{cases} \ddot{x}_{ides} = -\frac{1}{h}(\dot{\varepsilon}_i + \lambda\delta_i) \\ \delta_i = x_i - x_{i-1} + L + h\dot{x}_i \end{cases} \tag{3}$$

takes advantage of the relative speed and contains an extra term to fulfill time headway control. It has been proven that this control law can guarantee string stability (Darbha and Rajagopal 1999) and thus becomes a promising alternative to the constant space headway law.

Variable Time Headway (VTH) control (Wang and Rajamani, 2001) takes the relative velocity into account in the desired spacing, which is given by as follows:

$$\delta_i = \varepsilon_i + \frac{1}{\rho_m(1 - \dot{x}_i / v_f)} + b\dot{\varepsilon}_i \tag{4}$$

$$\ddot{x}_{ides} = -\rho_m(v_f - \dot{x}_i)(1 - \dot{x}_i / v_f)(\dot{\varepsilon}_i + b\ddot{\varepsilon}_i + \lambda\delta_i) \tag{5}$$

Where, ρ_m is the maximum density of the highway, at which point traffic will stop (we assume $\rho_m = 1/l$, l is the uniform vehicle length); v_f is the free flow speed; $\dot{\varepsilon}_i = \dot{x}_i - \dot{x}_{i-1}$ is the relative velocity between *i*th vehicle and *i-1*th vehicle; b is a positive coefficient which determine the how much the relative velocity contributes to the desired spacing.

(c) Car-following Model

Many models are developed to emulate the human driver's driving behavior, such as the GM model, Greenshield's model, Drew's model and Gipps' model (Gipps 1981). In our simulation, we use Gipps' Model to represent the acceleration and deceleration of manually controlled vehicles. This model states that, in any case, the definitive speed for vehicle n during time interval (t, t+T) is the minimum of those previously defined speeds:

$$V(n, t+T) = \min\{V_a(n, t+T), V_b(n, t+T)\} \tag{6}$$

where $V_a(n, t+T) = V(n,t) + 2.5a(n)T\left(1 - \frac{V(n,t)}{V^*(n)}\right)\sqrt{0.025 + \frac{V(n,t)}{V^*(n)}}$ (7)

$$V_b(n, t+T) = d(n)T + \sqrt{d(n)^2T^2 - d(n)\left[2\{x(n-1,t) - s(n-1) - x(n,t)\} - V(n,t)T - \frac{V(n-1,t)^2}{d'(n-1)}\right]} \tag{8}$$

V(n,t) is the speed of vehicle n at time t;
V*(n) is the desired speed of the vehicle (n) for the current section;
a(n) is the maximum acceleration for vehicle n;
T is the reaction time = updating interval = simulation step.
d(n) (< 0) is the maximum deceleration desired by vehicle n;
x(n,t) is position of vehicle n at time t;

x(n-1,t) is position of preceding vehicle (n-1) at time t;
s(n-1) is the effective length of vehicle (n-1);
d'(n-1) is an estimation of vehicle (n-1) desired deceleration.

The original version of Gipps' model doesn't have a mechanism for achieving a specific time headway. In the simulation, we added a time headway term that can affect the speed of vehicle to realize the headway control, i.e. {if (space headway)/(speed of following vehicle) < (desired time headway), then (the definitive speed) <= (current speed)}. This modified Gipps' model is more realistic with respect to the real condition that most drivers adjust their speeds according to estimated time headway (Koppa, 1998).

Traffic Simulation Program

A microscopic simulation program is developed in C++. There is a main cycle of calculation in which the states of vehicles and the traffic flow are updated in a single sampling time duration. The main cycle includes: (a) Vehicle entry procedure that determines whether a new vehicle should enter the road. ACC vehicles enter the traffic flow following a uniform distribution.(b) Vehicle exit procedure that determine whether the leading vehicle should exit from the road. If so, it deletes the leading vehicle and modifies the second vehicle to be the leading vehicle. (c) Vehicle state calculation block updates the states of each vehicle in current sampling duration. The car dynamics function will call the Runge Kutta algorithm (Press et al. 1992) that solves the differential equations. (d) Road state calculation procedure gets the instantaneous mean density, space mean speed, inflow rate etc. in the current sampling time.

Traffic Simulation Results

The scenarios discussed above are simulated in the program we developed. The results of simulations are summarized below.

Single Vehicle Following Behavior

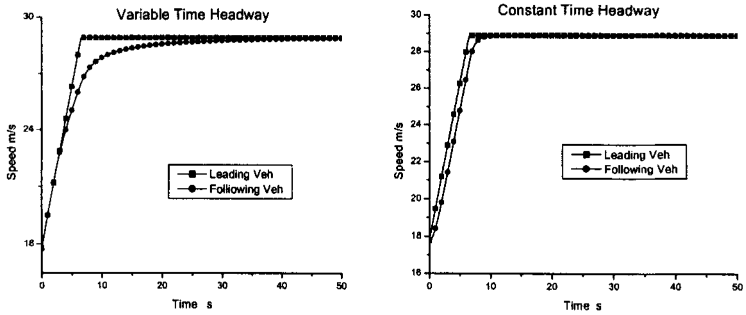


Figure 1. Single Vehicle's Following Behavior

The single vehicle following behavior includes the behaviors of vehicles with various controls under different settings. The typical single car following behaviors is shown in Figure 1. In these simulations, the preset time headway of CTH vehicle is 1 second. The two vehicles in the pair start up with the same initial speed and with a 20 meters distance. It is shown that vehicle controlled by VTH has slower response and a relatively long time to get to steady state. On the other hand, all vehicles can ultimately attain enough distance and maintain the constant time-headway. For CTH vehicles, it happens shortly after the arrival of the following vehicle. For VTH vehicles, it happens after two vehicles get to the maximum speed.

Speed Profiles of Traffic Flow with Different ACC Penetration

Under different constant demands, the mixed traffic of VTH cars performs better than those of CTH cars. As shown in Figure 2, under the same demand, the speed of VTH traffic is always higher than CTH traffic except the 100% case, as shown in Figure 3, and they always have shorter response time to reach the steady state. The speed discussed here is the space mean speed in the equilibrium state. The mixed traffic has larger speed oscillations than the cases of pure ACC traffic or pure manual traffic. This effect is more serious if the proportion is very high (greater than 95%). On the other hand, a little higher speed variance is found with VTH vehicles, as shown in Fig. 4. But this phenomenon is reversed in the cases of very high ACC penetration, such as 99% and 100%.

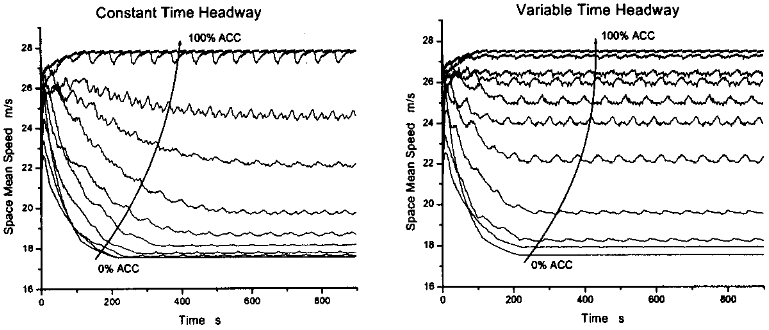
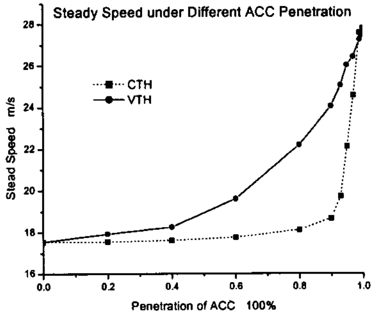


Figure 2. Speed Profiles of CTH and VTH ACC



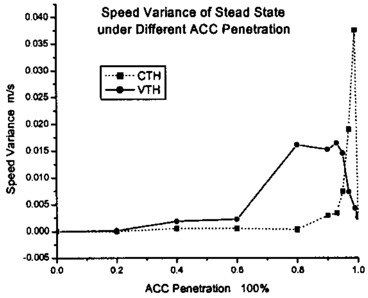


Figure 3. Speed of CTH and VTH

Figure 4. Speed Variance of CTH and VTH

System Response to External Pulse

A robust system is defined as a system that behaves in a controlled and expected manner when expected variations arise in its dominant parameters, but also in the face of unexpected variations (EASi GmbH 2001). In traffic systems, typical variations include the acceleration noise of vehicles, internal disturbances such as the sudden braking of a vehicle in the string and external disturbances such as the change of demand at the entry of the road. We expect that traffic is robust so that it can restore its normal condition after being disturbed by internal or external noise or disturbances. What we are most interested in is the response of the mixed traffic to an external disturbance that is generated by a pulse demand, which suddenly increases the demand for a short time. After imposing the same disturbances in the system with different ACC vehicle penetrations we can compare the result speed profiles and get the impacts of ACC on the mixed traffic, as shown in Figure 5. As we can see, the penetration of ACC will significantly affect the speed profiles:

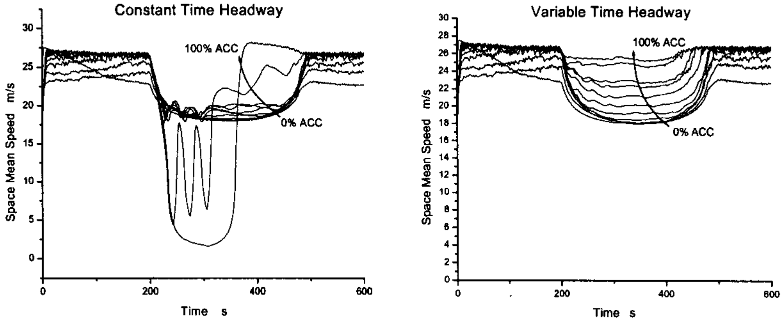


Figure 5. Speed Profiles of Traffic Flow with Different ACC Penetration

(a) The system restores to the normal state more quickly with higher VTH car penetration than with CTH.

(b) High penetration of VTH cars can reduce the system density and the speed drop during the pulse compared to a similar penetration of CTH cars. Under high demand, the drop of space mean speeds of the VTH traffic in the disturbance are always smaller than manual traffic and can easily return to normal after the pulse, while CTH traffic may experience serious speed drop that is even worse than that of pure manual traffic.

Density-speed and Density-Flow Rate Relation in Mixed Traffic

The typical relationships among density, flow rate and space mean speeds are meaningful in analyzing the impacts of ACC on the traffic system. In our work, two types of these relations are result from the simulation results.

The first k-v and k-q relations are obtained from the dynamic process that the system encounters a saddle demand, which is comprised of a linearly increasing part (150 seconds) and a linearly decreasing part (150 seconds). Figure 6 and 7 show the k-q and k-v curves for a 100% ACC system that encounters an over-capacity demand. For CTH traffic, it is shown that k-q curve is linear below capacity, and descends and ascends in the saddle demand part. In contrast, the k-q curve is nearly linear for VTH traffic. That means a VTH system can keep the free-flow speed in a longer range.

Figure 7 compares the k-v curves of VTH and CTH traffic encountering an over-capacity saddle demand. It is shown that VTH traffic has a higher speed and lower density than CTG traffic. Under the condition of very high demand inflow, VTH traffic decreases the speed and maintains the density until the demand is released, as shown in Fig. 8. The response process is shown in Fig. 9. As one can see, the system stops to accommodate more vehicles after the speed gets to a low point. In this case, the inflow rate is not the indication of the demand but the reflection of system capacity.

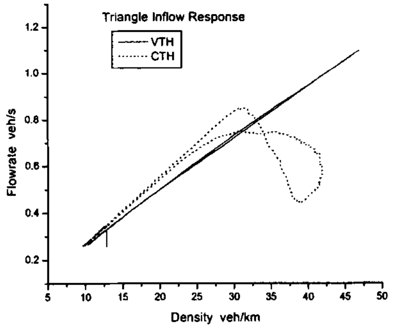


Figure 6.

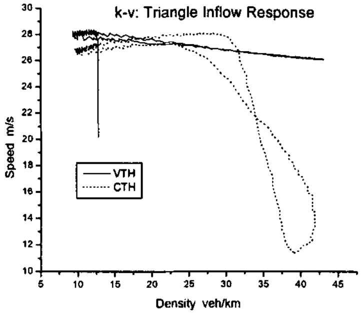


Figure 7.

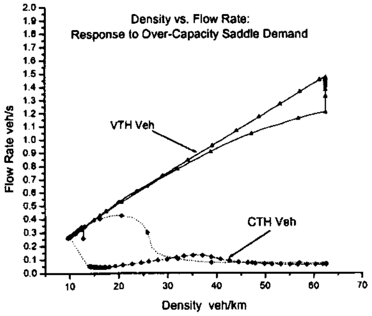


Figure 8.

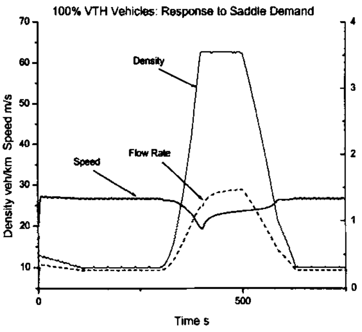


Figure 9.

Conclusions

To evaluate the impacts of ACC on the traffic flow and to find better ACC algorithms, we designed an environment to implement microscopic level simulation of mixed traffic. The performance of mixed traffic is simulated in every level of the traffic system, from a single car's following behavior to macroscopic traffic characteristics. These simulations provide a basis of evaluating safety, efficiency and cost/benefit of the system. Some realistic conclusions can be drawn from the simulation results. It is observed that the presence of ACC vehicles helps increase the space-mean speed of the system, which is a mark of system efficiency, but CTH vehicles may lead to a speed drop in the case of high demand while VTH mixed traffic always performs well. If we use VTH to achieve high speed, we find, it is at the expense of higher speed oscillation at above capacity inflow rates. From a traffic flow perspective, CTH control is potentially worse under select conditions than no ACC at all. VTH is a promising alternative of CTH as it is not detrimental to traffic flow when high demand is present.

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