Evaluation of Adaptive Cruise Control in Mixed Traffic

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Abstract: This paper discusses the impacts of Adaptive (Intelligent) Cruise Control (ACC) laws on traffic flow. Vehicles equipped with ACC, 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.

Keyword: Adaptive Cruise Control, Intelligent Cruise Control, Mixed Traffic, Constant Time Headway, Variable Time Headway

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1.   INTRODUCTION

Vehicles equipped with Adaptive (Intelligent) Cruise Control (ACC), with the capability to follow each other automatically in the same lane are expected to improve traffic flow on existing roadways. Research on the properties of automated-vehicle platoons has shown the potential benefits for capacity and safety (1; 2; 3). It seems an appealing scenario that all 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. Their results are meaningful for traffic operators to outline the potential impacts of ACC. However, the traffic flow characteristics that ACC will produce are difficult to quantify. Simulation results largely depend on the mechanics of the traffic model (4), and it is not possible to make direct comparison of previous research, because these studies have employed different ACC algorithms, different driver behavior models and a different driving environment.

Our research (20) begins with a simplified scheme. 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. The second section discusses the methodology for evaluating the impacts of different 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

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a microscopic traffic simulation program. We summarize the simulations on different levels 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 paper (20).

2.   SIMULATION OF MIXED TRAFFIC

2.1   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 study, Constant Time Headway (CTH) control and Variable Time Headway (VTH) ACC algorithms (Wang and Rajamani, 2001) were selected. A simple scenario of a one-lane highway section, 3.2 km long, with one entry and one exit was established. To simplify the analysis and interpretation, no lane changing is considered in this simulation work. To further simplify the simulation, a single lane scenario is adopted. The lane-changing behavior of ACC vehicle is so complicated that there is no mature model to describe it. 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:

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(a) No-ACC traffic: All vehicles on the road are controlled by Gipps' car-following model (5). 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 all 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 presets the headway and the desired speed that is constrained by the maximum speed in this section of highway.

2.2   Dynamic Models Of The Components Of Mixed Traffic

(a) *Vehicle Dynamics:*

The vehicle dynamics are 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 ACC algorithm that is first studied is **Constant Space Headway control:**

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

where L is the length of vehicle. It has been proven that this control law cannot guarantee string stability (6). So we do not pursue this control law.

Constant Time Headway (CTH) control is:

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

where h is the preset time headway; λ is the parameter of the controller in 1/second^2. This algorithm 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 (6) and thus becomes a promising alternative to the constant space headway law.

Variable Time Headway (VTH) control (7) takes the relative velocity into account in the desired spacing, which is given 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 ith vehicle and i-1th vehicle; b is a positive coefficient which determines how much the relative velocity contributes to the desired spacing. There is no minimum time headway in VTH. It always changes with inter-

vehicle spacing and speed. Its minimum space headway is the length of vehicle, but the speed in that case is close to zero.

(c) *Car-following Model*

Many models have been developed to emulate the human driver's driving behavior, such as Greenshield's model (15), Drew's model (16) and Gipps' model (5). Bengtsson (8) provides an overview of driver modeling. In this simulation, we use Gipps' Model to represent the acceleration and deceleration of manually controlled vehicles because it is used in commercial traffic simulation software with which we can compare and calibrate the simulation result. The further results are not included in this paper. This model states that the definitive speed for vehicle n during time interval (t, t+T) is the minimum of those previously defined speeds:

$$\dot{x}(n,t+T) = \min\{\dot{x}_a(n,t+T), \dot{x}_b(n,t+T)\} \tag{6}$$

$$\dot{x}_a(n,t+T) = \dot{x}(n,t) + 2.5\ddot{x}(n)T\left(1 - \frac{\dot{x}(n,t)}{\dot{x}^*(n)}\right)\sqrt{0.025 + \frac{\dot{x}(n,t)}{\dot{x}^*(n)}} \tag{7}$$

$$\dot{x}_b(n,t+T) = d(n)T + \sqrt{d(n)^2 T^2 - d(n)\left[2\{x(n-1,t) - s(n-1) - x(n,t)\} - \dot{x}(n,t)T - \frac{\dot{x}(n-1,t)^2}{d^\cdot(n-1)}\right]} \tag{8}$$

where: $\dot{x}$ (n,t) is the speed of vehicle n at time t;

$\dot{x}^*$(n) is the desired speed of the vehicle (n) for the current section;

$\ddot{x}$ (n) is the maximum acceleration for vehicle n;

T is the reaction time of driver, which equals to updating interval and 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 affects the vehicle speed 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 as most drivers adjust their speeds according to estimated time headway (9).

2.3   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.

- A 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.

A vehicle state calculation block updates the states of each vehicle in the current sampling duration. The car dynamics function will call the Runge Kutta algorithm (10) that solves the differential equations. The Runge-Kutta method is a conventional method of numerically integrating ordinary differential equations.

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- Road state calculation procedure gets the instantaneous mean density, space mean speed, inflow rate etc. in the current sampling time.

3. TRAFFIC SIMULATION RESULTS

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

3.1 Speed Profiles of Traffic Flow with Different ACC Penetration

Under constant demands, the mixed traffic of VTH cars performs better than those of CTH cars. As shown in Figure 1, under the same demand, the equilibrium space mean speed of VTH traffic is always higher than CTH traffic except the 100% case, and VTH always has a shorter response time to reach steady state.

After reaching the steady state, the mixed traffic has larger speed oscillations than 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 somewhat higher speed variance is found with VTH vehicles, as shown in Fig. 2. But this phenomenon is reversed in the cases of very high ACC penetration, such as 99% and 100%.

3.2 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 (11). In traffic systems, typical variations include the acceleration

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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. We are most interested in 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 3. As we can see, the penetration of ACC will significantly affect the speed profiles:

(a) The system returns 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 minimize 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 a serious speed drop that is even worse than that of pure manual traffic.

3.3   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 result from the simulation.

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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 10). Figure 4(a) and (b) 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 over a longer range. Figure 4(b) 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 CTH 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. 5(c). The response process is shown in Fig. 5(d). 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.

3.4   Simulation with Some Random Effects

As a simplified analysis, the previous simulations do not include the variation of headways among ACC and manual vehicles. To make the simulation more realistic, a randomly chosen headway is implemented in simulation, which is consistent with the approach taken by some early research (17, 18 and 19). It is assumed that drivers keep their favorite headway all the time. Though it is still a simplified situation, its result is important in that it separates the impacts of drivers' personal headway choices so we can

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compare them with the former results we obtained. The time headway of Gipps' vehicle is normally distributed with mean=2 sec and a given standard deviation and a 1-second minimum. Time headway of CTH vehicle is normally distributed with mean=1 sec and a given standard deviation and a 0.8-second minimum. Experimental results are summarized below:

Mixed traffic of CTH and manual vehicles

Five combinations of ACC and manual vehicles with different headway distributions are simulated. Three scenarios are used to compare the impacts of headway deviation of human driver, which include:

(1) CTH=1 sec; Gipps= 2 sec, as shown in Figure 5(a);

(2) CTH=1 sec; Gipps= max(2+ N(0,1), 1) sec, as shown in Figure 5(b);

(3) CTH=1 sec; Gipps= max(2+ N(0,1)*2, 1) sec, as shown in Figure 5(c);

Two scenarios are used to compare the impacts of headway deviation of ACC vehicles, which include:

(4) CTH= max(1.0+ N(0,1)/2, 0.8) sec; Gipps= max(2+ N(0,1)*2, 1) sec, as shown in Figure 6(a);

(5) CTH= max(1.0+ N(0,1)/4, 0.8) sec; Gipps= max(2+ N(0,1)*2, 1) sec, as shown in Figure 6(b);

where N(0,1) is a normal distribution with mean = 0 and deviation = 1.

The random headways of manual vehicles do not have much influence on the performance of traffic. In contrast, the random headways of CTH ACC vehicles greatly affect traffic. Higher headway deviation of CTH vehicles will lead to a greater speed drop and oscillations, especially when the ACC penetration is very high.   In the case of

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100% CTH ACC penetration, higher headway deviation results in serious speed drop and longer time to recover.

Figure 7(a) presents the comparison of the average speed in the five CTH experiments; Figure 7(b) presents the comparison of the speed variance. As one can see, high penetration of CTH ACC increases the average speed in most cases. But high headway deviation diminishes this effect. On the other hand, the speed variance is not significant in most cases, except the case of 100% ACC penetration under high headway deviation. It can be concluded that these results cannot provide support to the claim that CTH ACC will add traffic capacity.

Mixed traffic of VTH and manual driven vehicles

Three combinations of VTH and manual vehicles with different headway distributions are simulated, which include:

(1) VTH and Gipps = 2 sec, as shown in Figure 8(a);

(2) VTH and Gipps = max(2+ N(0,1), 1) sec, as shown in Figure 8(b);

Because VTH does not have preset headway, its headway is always in changing. The only random factor here is the random headway of human drivers in manual vehicles. It is shown that VTH ACC always performs well facing different headway deviation of human driver.

Figure 9(a) presents the comparison of the average speed in the three VTH experiments; Figure 9(b) presents the comparison of the speed variance. There is no significant difference in terms of speed and speed variance. These results further support the advantage of VTH ACC compared with CTH ACC.

4. 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. These simulations provide a basis of evaluating safety, efficiency and cost/benefit of the system. 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 to CTH as it is not detrimental to traffic flow when high demand is present. There is a safety concern about VTH, Wang and Rajamani illustrated the inter-vehicle spacing of VTH and CTH in (7) and shows that VTH is a safe control strategy.

All of the conclusions drawn above should be conditional and tentative because many assumptions are used to idealize the system to make it computationally feasible. We note that the headway errors of vehicles can be seen as a source of the disturbance generated in the traffic flow. After we simulate situations in which ACC and manual vehicles have different distributions of preset headway, it is concluded that the headway deviation doesn't have much impact on the traffic performance in most of situations.

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List of tables and figures:

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Figure 1. Speed Profiles of CTH and VTH ACC

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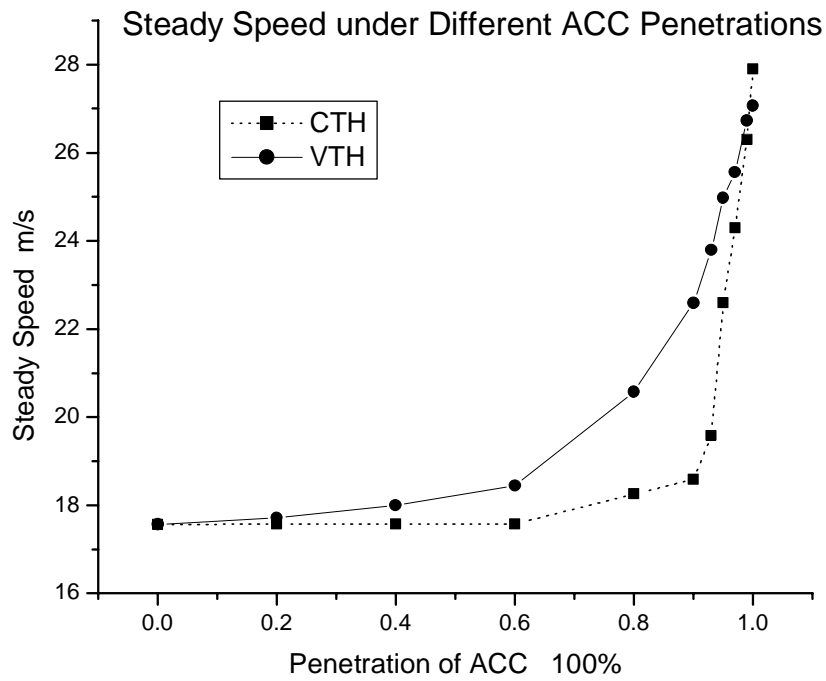
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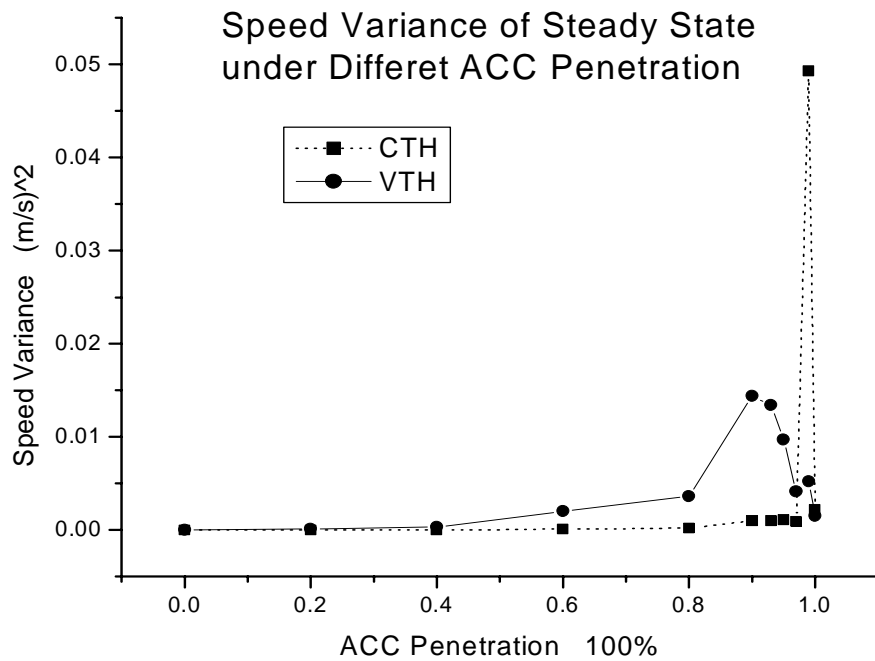
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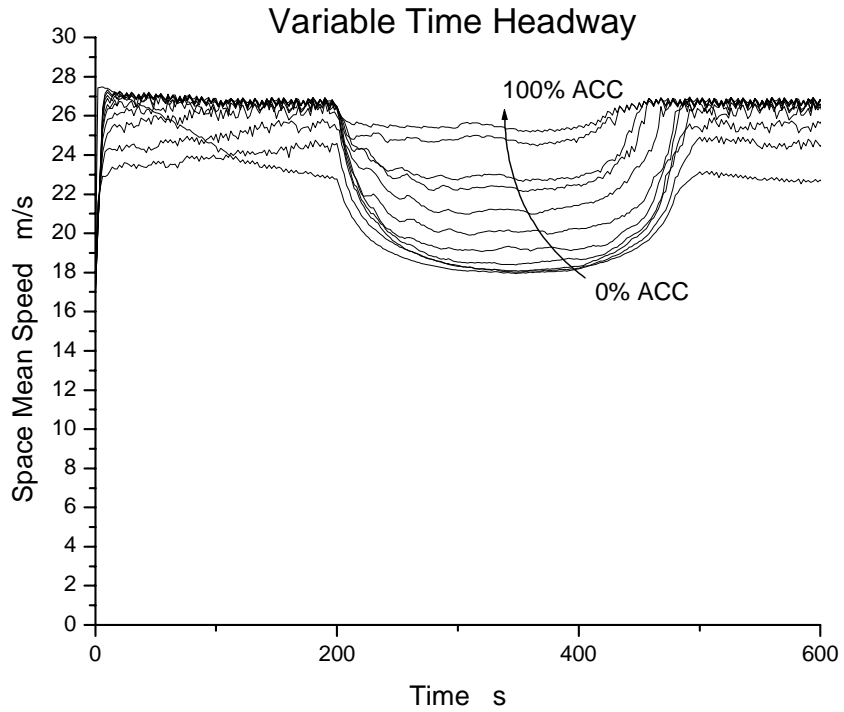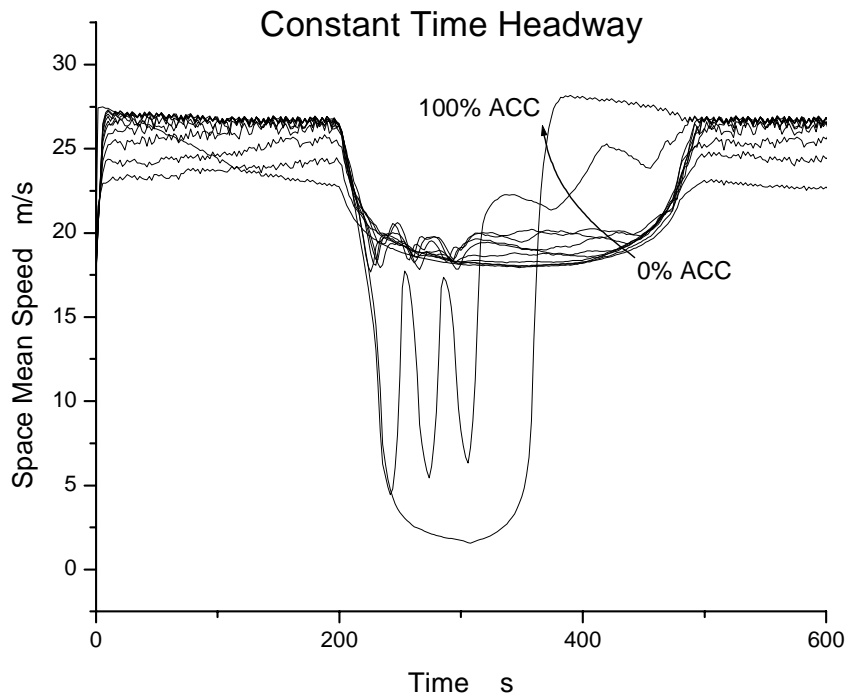
Figure 3. Speed Profiles of Traffic Flow with Different ACC Penetrations
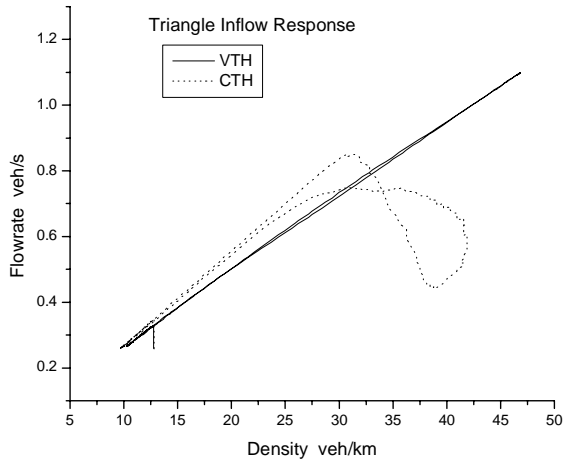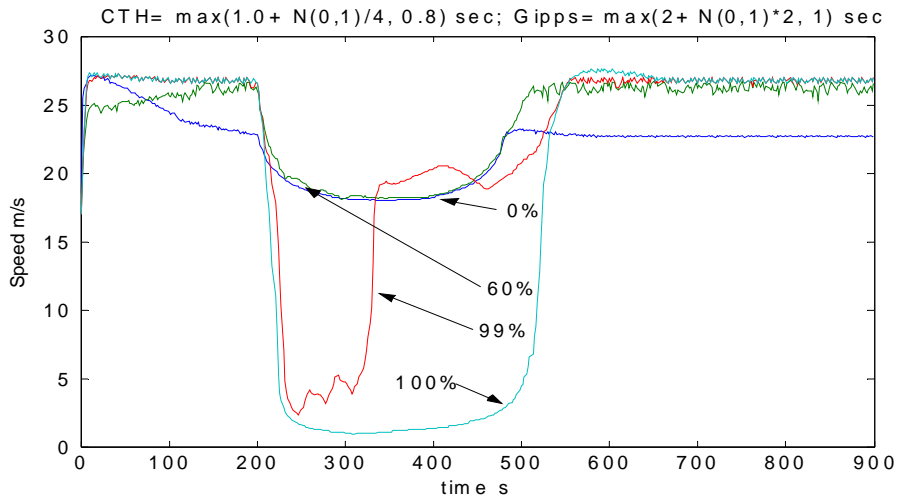
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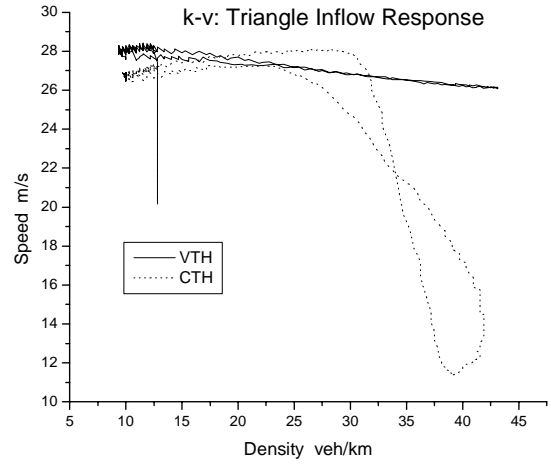
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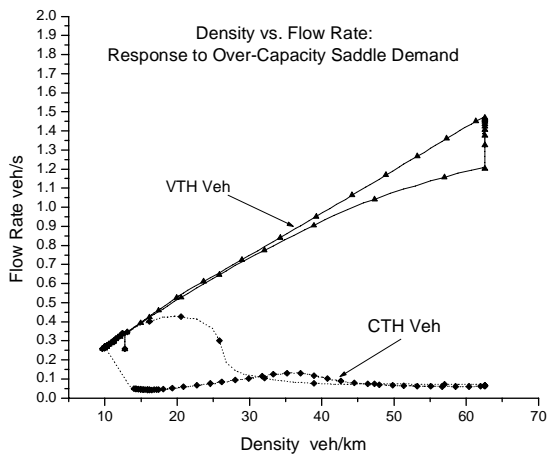
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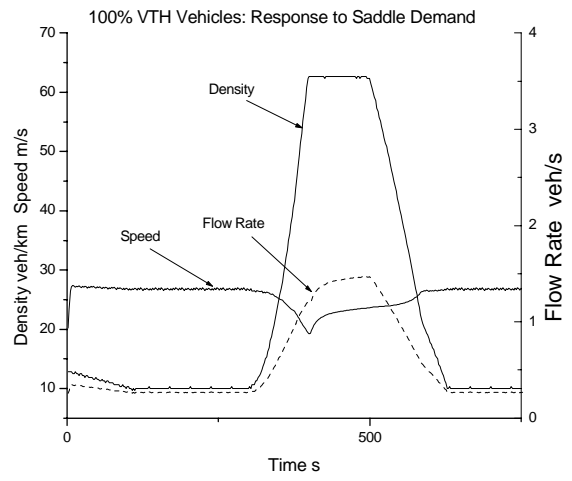
(d)

Figure 4. Comparisons of VTH and CTH

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CTH= 1 sec; Gipps= 2 sec

(a)

CTH= 1 sec; Gipps= max(2 + N(0,1), 1) sec

(b)

CTH= 1 sec; Gipps= max(2 + N(0,1)*2, 1) sec
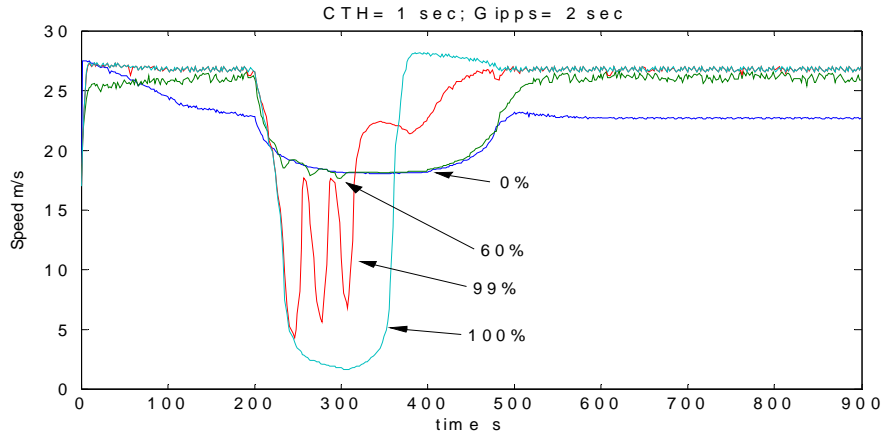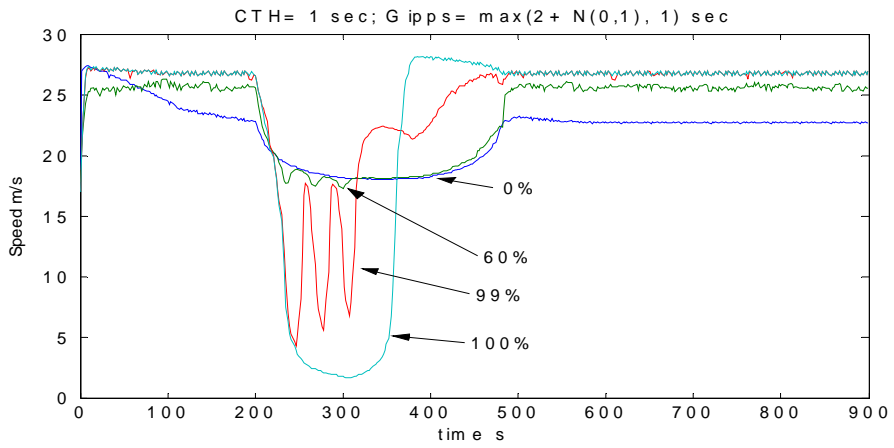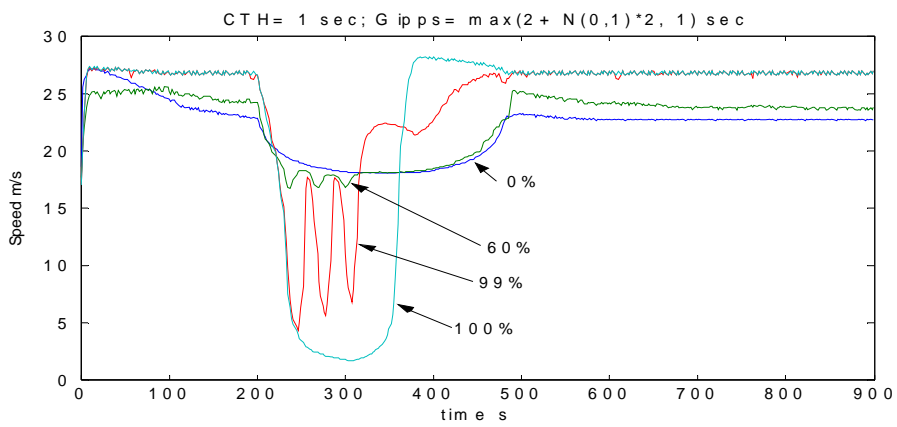
(c)

Figure 5. Simulation with stochastic driver headways

CTH= max(1.0+ N(0,1)/4, 0.8) sec; Gipps= max(2+ N(0,1)*2, 1) sec

(a)

CTH= max(1.0+ N(0,1)/2, 0.8) sec; Gipps= max(2+ N(0,1)*2, 1) sec
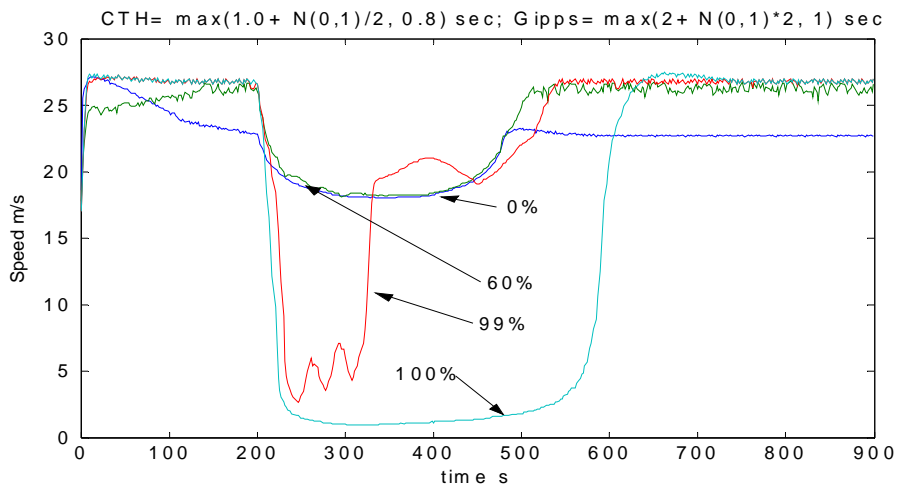
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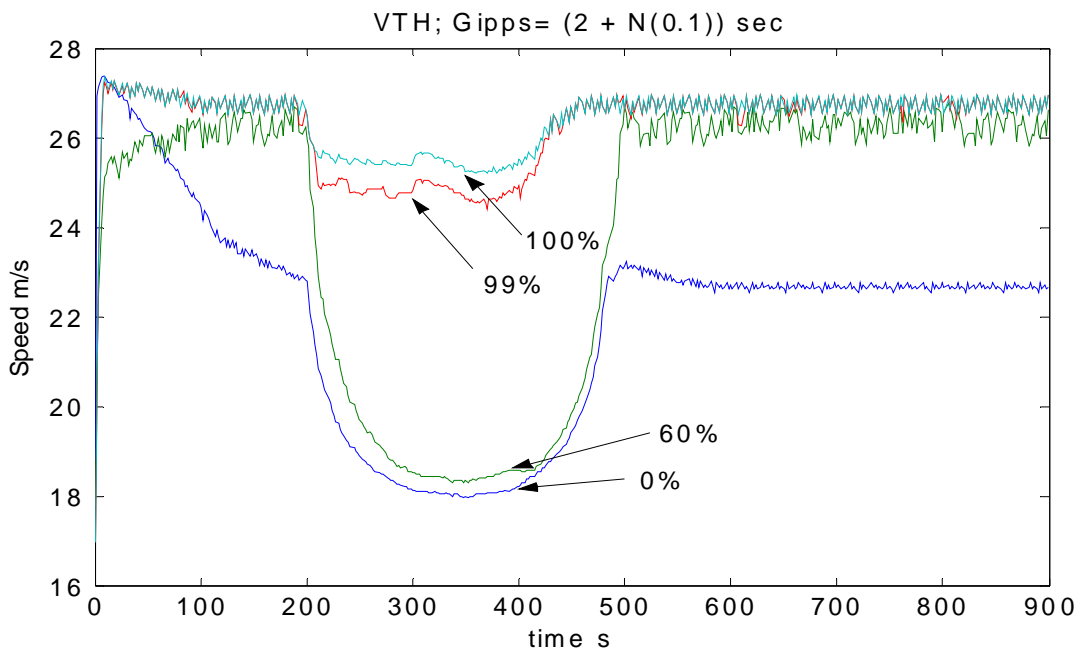**Figure 6. Simulation with stochastic ACC and driver headways**
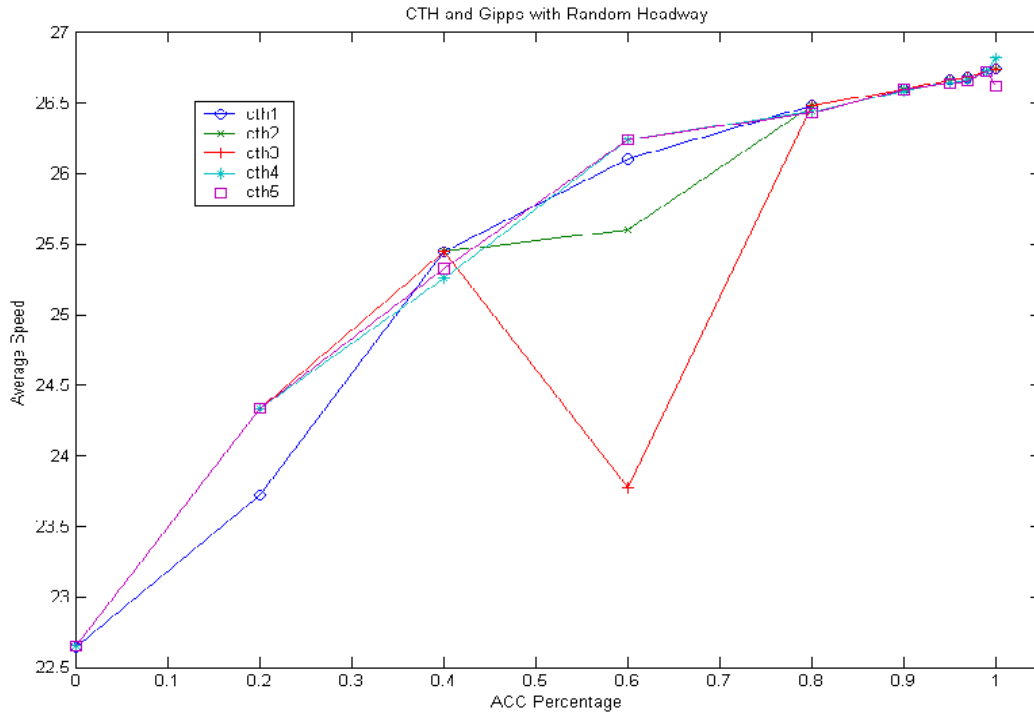
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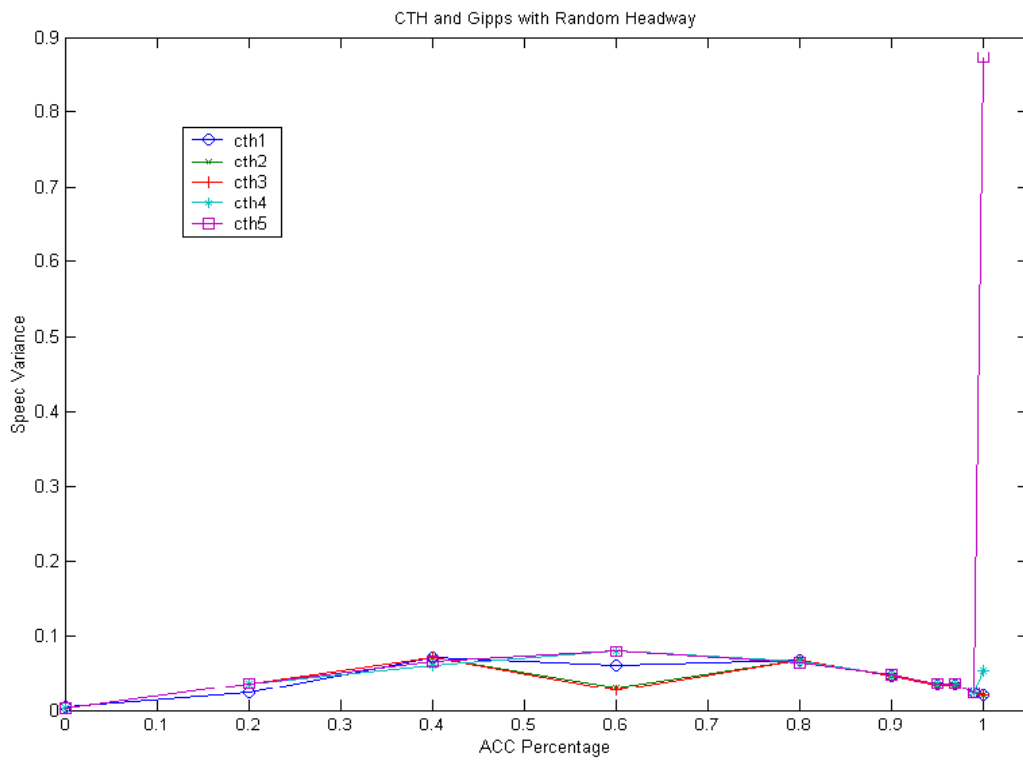
(b)

Figure 7. Speed and speed variance of mixed traffic (CTH)

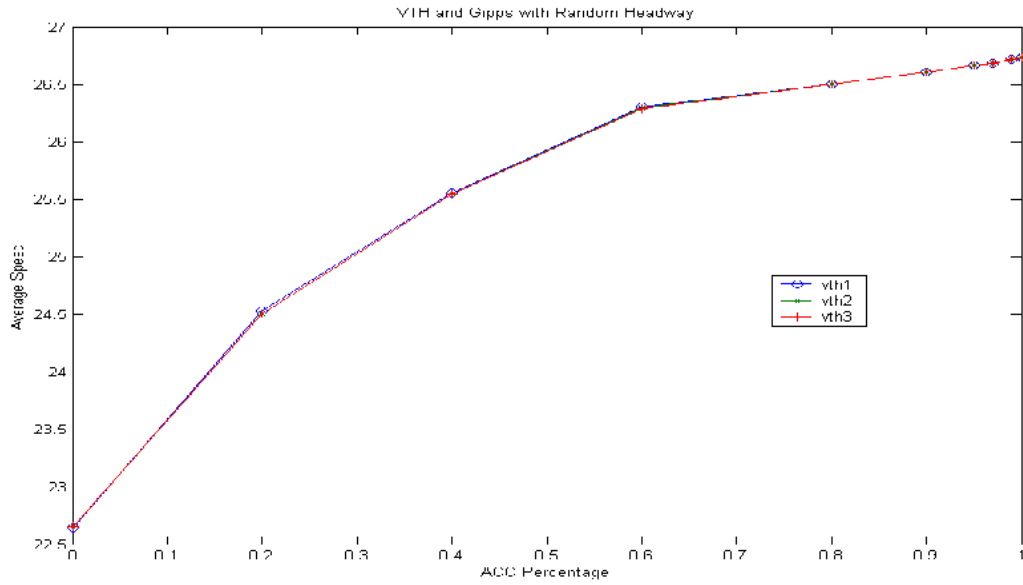TRB 2003 Annual Meeting CD-ROM   Paper revised from original submittal.
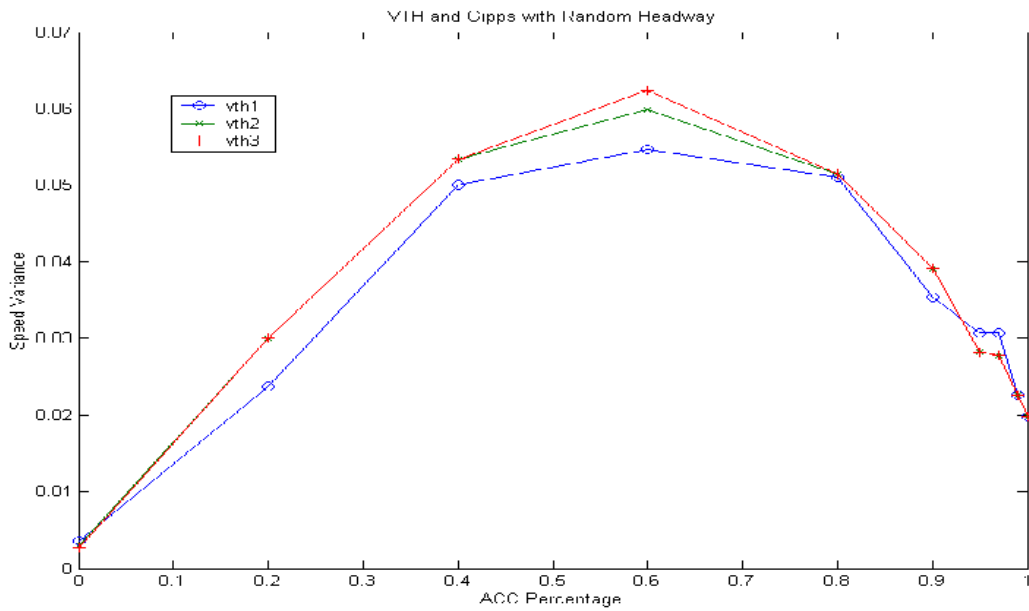
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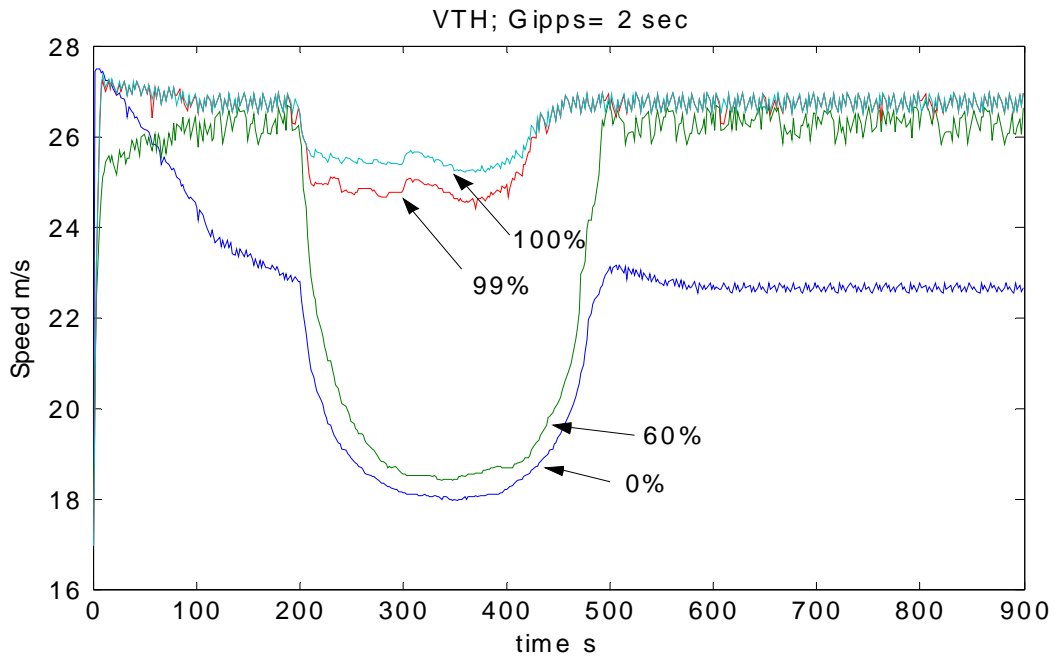
(a)

(b)

Figure 8. Mixed traffic of VTH ACC and stochastic driver headways
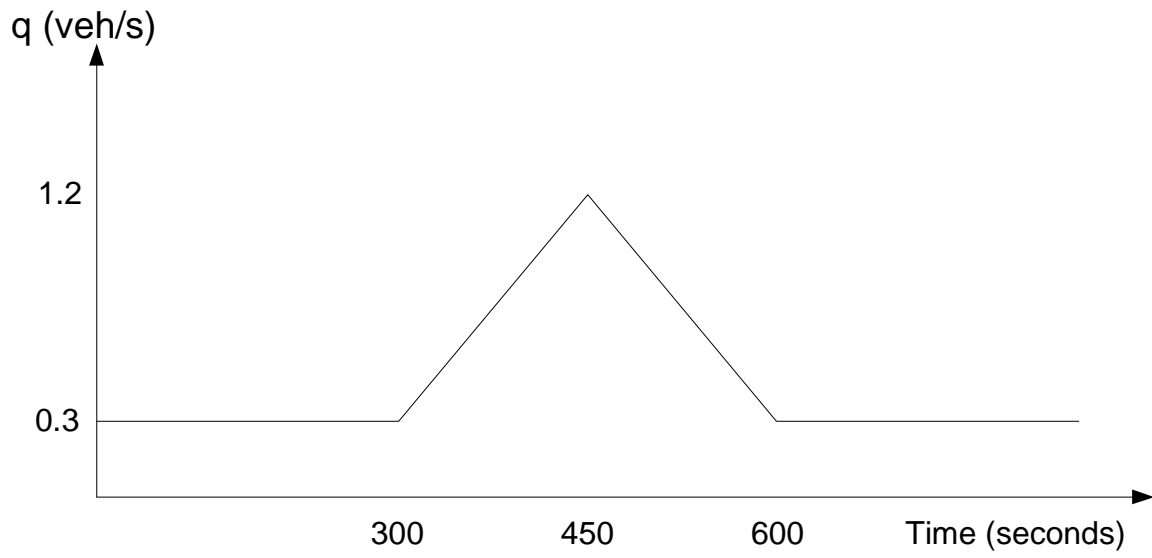
(a)

(b)

Figure 9. Speed and speed variance of mixed traffic (VTH)

Figure 10. An example of Saddle Demand