

Simulation and Analysis of Mixed Adaptive Cruise Control / Manual Traffic

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ABSTRACT

Semi-automated vehicles, such as Adaptive (Intelligent) Cruise Control (ACC) Vehicles, with the capability to 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 are presented. The analysis of the effect of mixing on capacity and stability of traffic system is based on these results. It's found that throughput increases with the proportion of ACC vehicles when flow is below capacity conditions. But above capacity, speed variability increases and speed drops with Constant Time Gap (CTG) control ACC compared with human drivers.

KEY WORDS: Adaptive Cruise Control, Vehicle Highway Automation, Traffic Flow, Evaluation, Mixed Traffic

1. INTRODUCTION

Vehicle manufacturers hope that semi-automated vehicles with the capability to follow each other automatically in the same lane will improve the traffic flow on existing roadways. Research on the properties of automated-vehicle platoon has shown the potential benefits for capacity and safety (Van Arem et al. 1996; Broqua et al. 1991; Minderhoud and Bovy 1998). More than half of the interstate accidents are attributable to driver actions (1994 Interstate Hazard Analysis) 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 at the initial stage of deploying automated or semi-automated vehicles, they

will coexist with conventional manually driven vehicles. The so-called automated vehicles should be equipped with advanced sensing, communication and control systems that allow them to run without command from human drivers. The semi-automated vehicles, such as Adaptive (Intelligent) Cruise Control (ACC) Vehicles, can implement simple following operations while keeping safe distances. A mixed control scenario raises complex capacity and safety issues that we must probe before ACC becomes reality.

While the main concerns of the automakers are drivers' comfort, safety and production cost, traffic operators are concerned with the impacts of such new equipment on safety and traffic capacity. On the other hand, the designers of ACC algorithms often consider the "string stability" as the primary criterion (Darbha and Rajagopal 1999, Fancher and Bareket 1995, Li and Shrivastava 2001). Many simulation studies have evaluated the impacts of ACC systems (Van Arem et al. 1996; Broqua et al. 1991; Minderhoud and Bovy 1998). However, the traffic flow characteristics that ACC will bring are difficult to quantify. And it's not possible to make direct comparison among these documents, because these studies have employed different ACC algorithms, different driver behavior models and different driving environment. What we can do is to find some common trend and make some qualitative explanations. In their work, Broqua et al. (1991) estimated that gains in throughput are 13% with 40% of vehicles equipped with constant-space-gap ACC when the target time-gap of the system was 1 second. Van Arem et al. (1996) and Minderhoud and Bovy (1998) have found a decrease in average speed caused by a collapse of speed in the fast lane for ACC target time-gaps of 1.4 s and above.

Because of some advantages to fuzzy logic models, Wu et al. (1998) gave a complete description of the fuzzy sets for both car following and lane changing in FLOWSIM which offers a user defined update rate and applies accelerations. The fuzzy inference model for car following is based on two variables: (1) distance divergence of the ratio of vehicle separation to desired vehicle separation; and (2) the relative speed of the driver's vehicle to the lead vehicle. Similar work can be found in Chakroborty et al. (1999), in which relative speed, distance headway and acceleration/deceleration rate of leading vehicle are the inputs to a fuzzy logic model. Marsden et al. (2001) employed Wu's car following model in simulation. An ACC algorithm based on a manufacturer prototype was also employed in which the acceleration rate adopted by the ACC vehicle during a given period is related to

the following variables: vehicle mass, the gap headway, the rate of change of gap headway, velocity of the equipped vehicle. The results showed that following with ACC could reduce the variation of acceleration compared to manual driving. The authors also pointed out the limitations of microscopic simulation in modeling the impacts of ACC. Because of the lack of understanding of the interaction between the driver and the ACC system relative to the traffic conditions, microscopic simulation may not truly duplicate real traffic. All of this research provided the estimates of impacts of ACC in some specified situations. Because of the lack of theoretical tools to analyze this complex system, their results are meaningful for the traffic operators to outline the potential impacts of ACC system. 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.

In this paper, we first discuss the methodology and criteria that can be used to evaluate the impacts of one ACC algorithm on traffic flow. A number of cases with mixed ACC and manually controlled traffic are simulated and analyzed using a microscopic traffic simulation program. To simplify the analysis, a one-lane highway is studied. The semi-automated vehicles are equipped with an ACC algorithm that allows them to keep a constant time headway while following. Gipps' model (Gipps, 1981) is used to simulate manually driven vehicles.

The density and speed profiles as a function of the proportion of ACC vehicles are investigated, which show the potential benefits of the semi-automated vehicles. Different vehicle following scenarios with sudden decelerations and accelerations are analyzed in order to study the effect of the response of ACC vehicles in mixed traffic.

In section 2, we describe the mixed traffic scenario that is investigated. The simulation program is also elaborated in section 2. Section 3 summarizes the simulations on the different level of highway traffic as a function of the proportion of ACC vehicles. The stability and transient response of traffic flow in different mixed traffic situations are illustrated in the results. Some concluding remarks in section 4 complete the report.

2 SYSTEM CONFIGURATION: MIXED TRAFFIC SCENARIO

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, a Constant Time Gap (CTG) control ACC algorithm was selected. Although a number of driving simulator studies have been undertaken, these have necessarily focused on critical safety aspects of ACC use, such as Nilsson (Nilsson, 1995). Very few studies exist on how drivers incorporate the functionality of ACC into their driving cycle. For the purpose of this research, it has been assumed that if there is an ACC system equipped in the vehicle, it is used. However, according to the US Field Operational Test trials, ACC was used for just over 50% of all miles driven at speeds of above 35 mph. In addition, usage rates for individuals varied between 20% and 100% (Fancher et al. 1998). However, the purpose of the simulation is to define the range of traffic effects that could be found. So we don't stochastically change modes of control in our simplified simulations.

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. ACC vehicles are allowed onto the current highway system used by manually driven vehicles. Metering is done at the entrance to guarantee enough initial headway on the highway, and while waiting to enter the highway, ACC vehicles are treated just like manual vehicles.

The demand profile employed for the study was chosen it would result in an overloading of road capacity during the middle 150 seconds (from 200 to 350 second) of the simulation.

The maximum deceleration of the ACC equipped vehicle when under time headway control mode is limited to 2 m/s^2 while the maximum acceleration under ACC is 1.5 m/s^2 .

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. 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 safety and stability issues in this scenario are expected to be more complicated than others.

(c) Pure ACC traffic: All vehicles are controlled by ACC. It can be called semi-automated in which each vehicle individually assigns desired headway and desired speed.

The role of the driver of the semi-automated 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 is responsible for all driving functions as in a manually driven vehicle except for the longitudinal control. The vehicle has an automatic control system that controls the throttle and the brake actuators. 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.

2.2 DYNAMIC MODELS OF THE COMPONENTS OF MIXED TRAFFIC

The main dynamic models used in the simulation are the vehicle dynamics and the ACC algorithm.

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

$$\ddot{\dot{x}}_i = \frac{1}{t}(\ddot{x}_{ides} - \ddot{x}_i) \quad (1)$$

where: $\ddot{\dot{x}}_i$ 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 Gap** control, which is in form of:

$$\begin{cases} \ddot{x}_{ides} = -k_1 \mathbf{e}_i - k_2 \dot{\mathbf{e}}_i \\ \mathbf{e}_i = x_i - x_{i-1} + L \end{cases} \quad (2)$$

Though it takes advantages of the relative position and relative speed as the control input, it has been proven that this control law cannot guarantee string stability (Darbha and Rajagopal 1999). So we don't pursue this control law.

Constant time gap control, which is in form of:

$$\begin{cases} \ddot{x}_{ides} = -\frac{1}{h}(\dot{e}_i + \mathbf{I}d_i) \\ \mathbf{d}_i = x_i - x_{i-1} + L + h\dot{x}_i \end{cases} \quad (3)$$

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 gap law. In this paper, we use CTG control law as the primary one to test the impacts of ACC on the traffic flow.

(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, the maximum speed to which a vehicle (n) can accelerate during a time period (t, t+T) is given by:

$$V_a(n, t+T) = V(n, t) + 2.5a(n)T \left(1 - \frac{V(n, t)}{V^*(n)} \right) \sqrt{0.025 + \frac{V(n, t)}{V^*(n)}} \quad (4)$$

where:

$V(n, t)$ 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.

On the other hand, the maximum speed that the same vehicle (n) can reach during the same time interval (t, t+T), according to its own characteristics and the limitations imposed by the presence of the leader vehicle is:

$$V_b(n, t+T) = d(n)T + \sqrt{d(n)^2 T^2 - d(n) \left[2\{x(n-1, t) - s(n-1) - x(n, t)\} - V(n, t)T - \frac{V(n-1, t)^2}{d(n-1)} \right]} \quad (5)$$

where:

$d(n)$ (< 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.

In any case, the definitive speed for vehicle n during time interval $(t, t+T)$ is the minimum of those previously defined speeds:

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

Then, the position of vehicle n inside the current lane is updated taking this speed into the movement equation:

$$V(n, t + T) = x(n, t) + V(n, t + T)T \quad (7)$$

2.3 GENERATION OF TRAFFIC

As we have mentioned before, traffic generation complies with given traffic demand profiles. Normally, we use constant inflow rate or pulse inflow rate to test the system. Each vehicle entering the road is controlled by a mechanism that changes the initial headway according to the specific inflow rate at that time.

The other issue is to control the proportion of ACC vehicles. In our simulation, ACC vehicles are in traffic flow following a uniform distribution.

2.4 TRAFFIC SIMULATION PROGRAM

A microscopic simulation program is developed in C++. The flowchart of the program is shown in Figure 1. 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 sampling time is 0.1 second in our simulation. The main cycle includes:

(a) Vehicle entry procedure that determines whether a new vehicle should enter the road. If so, it generates a new vehicle with a randomly selected control law, either Gipps' model or ACC algorithm;

(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. In our simulation, the leading vehicle will be free to accelerate until it reaches the maximum speed;

(c) Vehicle state calculation calls the functions to update 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. Either Gipps' car-following model or ACC algorithm will generate the desired acceleration for each individual vehicle;

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

The important parameters used in the simulation are summarized in Table 1.

3. TRAFFIC SIMULATION RESULTS

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

(1) Single Vehicle Following Behavior

The single vehicle following behavior includes the behaviors of vehicles with various controls under different settings. Some typical results are shown in Figure 2. In these simulations, the preset time headway of an ACC vehicle is 1 second, while that of a Gipps' vehicle is 2 seconds. The two vehicles in the pair start up with the same initial speed and with a 20 meter distance. It's shown that ACC vehicles will have a quicker response and thus smaller transient time than manual vehicles. So in these scenarios, Gipps' vehicles cannot catch the leading vehicles because the leading vehicles are free to accelerate. In contrast, ACC vehicles can always maintain the constant time-gap. This result highlights an important advantage of ACC compared to manual vehicles: a small time headway is more easily realized by ACC vehicles; thus ACC vehicles generate capacity.

(2) Headway Response of Various Controlled Vehicles

The headway response is the basic behavior that impacts the safety and capacity of the road. We experimented with the response of ACC vehicles and Gipps' vehicles to the preset headway under car-following scenarios. The basic conditions include: (a) Two vehicles have the same initial speed (17.7 m/s); (b) The leading vehicle's initial position is

20 meters from the entry, while the following vehicle is located in the entry point; (c) The maximum speed for both vehicles is 28.9 m/s. 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).

Figure 3 shows the time headway response of ACC vehicle and Gipps' vehicle. The preset (desired) time headway changes from 0.1 second to 3 seconds, which is represented by the solid curve in each graph. In fact, headways under 0.5 seconds are rarely used because most drivers will change to space control under such conditions. But these simulations are meaningful to show the responses of these models in the emergent situations or in the case of congestion.

The real headway response is shown by the curve with marker in each graph. The figure shows that ACC vehicles can always achieve the preset headway with a small error. Changing the parameters of the algorithm cannot eliminate this error, which is largely from lack of an integral component in the controller. From (c) we see that the Gipps' vehicle cannot catch the ACC vehicle. That's because the ACC vehicles can get to the maximum speed more quickly. On the other hand, as shown in (d), the headway errors for Gipps' vehicles are quite large compared to ACC vehicles. Though it is an innate disadvantage of Gipps' model, we expect a similar number of errors for human drivers.

By comparing these results, we conclude that the headway response of ACC vehicles can fulfill the requirement that will potentially bring into potential of high capacity. The traffic flow comprised by these two kinds of vehicles is a mixed flow with heterogeneous headway behaviors.

(3) Robustness: System Response to Internal and External Pulse

A robust system is a system that can restore its normal condition after being disturbed by internal or external noise or disturbances. Formally, 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 can qualitatively judge the robustness of the traffic system by observing the profiles of flow, speed, and density.

The system response to an internal disturbance is shown in Figure 4. The internal disturbance is generated by a sudden braking of a vehicle in the string. After a while, the speed of that vehicle is restored to normal conditions. The vehicles behind the braking vehicle will be affected. As shown in Figure 5(d), which is the case of 100% ACC penetration, the speeds of some vehicle are reduced to maintain safe distances. After the speed of the leading vehicle is restored, the affected vehicles can return to normal speeds. Furthermore, the restored platoon is running under a one-second time gap, which is smaller than that of normal condition. So there is a capacity gain that can compensate the loss caused by braking. It should be noted that this gain could only be obtained when the normal running of traffic is below the capacity of the system. This result shows that CTG control ACC has the potential to stabilize the traffic under small disturbances.

What we are most interested in is the mixed traffic to the external disturbance that is generated by the pulse demand discussed in Chapter 2. This is because this kind of disturbance is a typical case in real traffic. The scenarios with different penetration of ACC are simulated and the results are shown from Figure 5. As we can see:

- (a) The densities and space mean speeds of the system in the disturbance are always within a boundary and can return to normal after the pulse.
- (b) The density-speed curves of these scenarios largely comply with an inverse proportional relation, while high penetration of ACC can increase the system speed in the pulse. (We discuss it further in section (4).)
- (c) The density-flow rate curves show a linear relationship in the uncongested region.
- (d) High penetration of ACC vehicles can reduce the system density and the speed drop during the pulse. This means there are potential capacity gains under high penetration of ACC vehicles.

(e) The mixed traffic has larger speed oscillations than the cases of pure ACC traffic or pure manual traffic. The oscillations may come from the different acceleration behaviours among ACC vehicles and manual vehicles.

(4) Speed Profiles of Traffic Flow with Different ACC Penetration

After exerting 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 6.

As we can see, the penetration of ACC will significantly affect the speed profiles:

(a) The system uses less time to get to the normal running state with higher ACC penetration;

(b) The system with higher ACC penetration uses less time to return to a normal state after a disturbance by the external pulse;

(c) The reductions of speed drop in the pulse are not linear with ACC penetration. The most remarkable change happens between 90% and 100% penetration. This means that high penetration of ACC can reduce speed loss.

(d) A questionable result in this graph is the speed profile with 100% ACC penetration. The Space mean speed increases instead of decreasing in the pulse. This is because a smaller portion of vehicles on the road are in the process of acceleration. As we can see in Figure 7, the proportion of low speed vehicle is zero in the peak of the speed profile. Thus a higher mean speed is obtained in the peak where most vehicles are in high speed. However, at the peak of the pulse, some vehicles cannot enter the system. They are queued at the bottleneck waiting to enter the system and are not counted.

(5) 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 8(a) shows the k-q and k-v curves for a

100% ACC system that encounters an over-capacity demand. It's shown that k-q curve is linear when flow is below capacity, and descends and ascends in the saddle demand part. In contrast, the k-v curve is nearly constant in under-capacity part. That means a pure ACC system can keep the free-flow speed before entering the congested region. Figure 8(b) compares the cases that 0% ACC system and 100% ACC system encounter at near-capacity saddle demand. It's obvious that 100% ACC system has a higher speed and lower density than a 0% ACC system.

(6) Influence of Headway of vehicles

Because we use constant time gap ACC in our simulation, the preset headway will determine the throughput of the system. Mean time headway can be computed as:

$$h_a = h_{acc}p + h_{man}(1 - p) \quad (8)$$

where: h_a : average headway

h_{acc} : headway of ACC vehicles

h_{man} : headway of manual vehicles

p : proportion of ACC vehicles

Throughput for semi-automated vehicles with ACC can be obtained from:

$$q = 3600/h_a \quad (9)$$

So we can increase the throughput by reducing the preset headway of ACC vehicles.

On the other hand, there is a serious disadvantage to constant time gap control. If the demand flow rate is higher than the inverse of the preset headway of ACC vehicles, a rapid drop of speed will happen, as we can see in Figure 9. In this case, the differences of the system in pulse with various proportions of Constant Time Gap control ACC vehicles are rather small and the benefits of high penetration of ACC are not remarkable.

(7) The variance of speed in the equilibrium state:

The ripples in the pattern of the speed can be evaluated by the variance. The speed discussed here is the space mean speed in the equilibrium state. It seems that CTG control ACC vehicles will generate more oscillations in the patterns of the speed, as shown in Figure 10. This effect is more serious if the proportion is very high (greater than 95%). In the stable range with low proportion of CTC vehicles, the variance is always small.

4 CONCLUSIONS

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 may lead into oscillations that may have negative fuel and environmental implications.

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. For instance, if we use a constant time gap algorithm to achieve high speed, we find that a high (95 ~ 99%) penetration of CTC vehicles increase throughput. But it's at the expense of high speed oscillation at above capacity inflow rates. From a traffic flow perspective, constant time gap control is potentially worse under select conditions than no ACC at all. This requires additional research into alternative control laws that are not detrimental to traffic flow before ACC should be deployed.

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Table1. Simulation Parameters of road and traffic flow:

Road length	3200 meters
Maximum size of vehicles	4 meters
Initial speed of vehicles	17.79 m/s (40 mph)
Maximum Speed	28.9 m/s (65 mph)
Desired Speed in Gipps' Model	28.9 m/s (65 mph)
Maximum Acceleration in Gipps' Model	1.7 m/s ²
Time Headway in Gipps' Model	2 second
Parameters of operation:	
Sample time (calculation cycle)	0.1 second
Simulation time duration	600 ~900 seconds
Maximum number of vehicles	200 (can be larger)

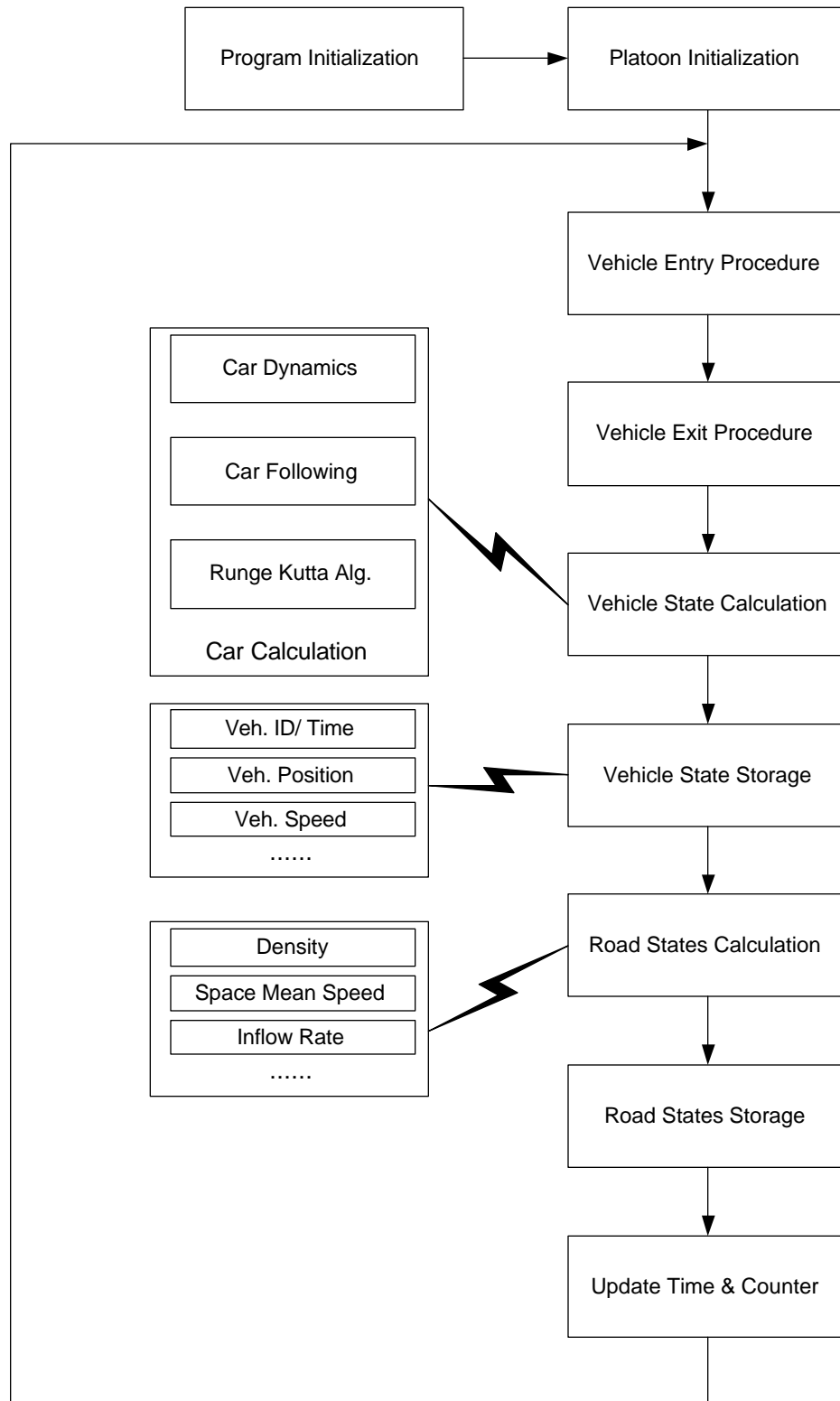
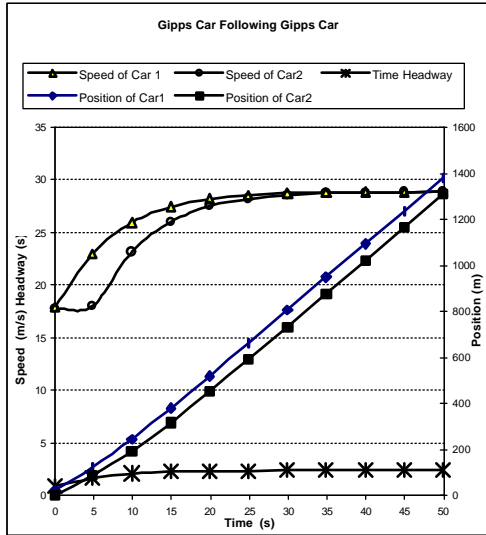
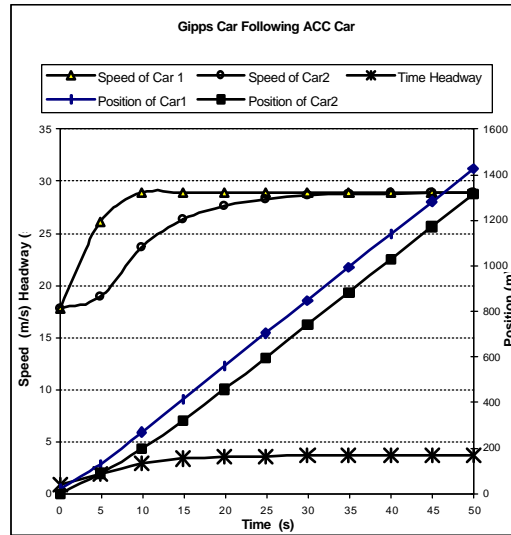


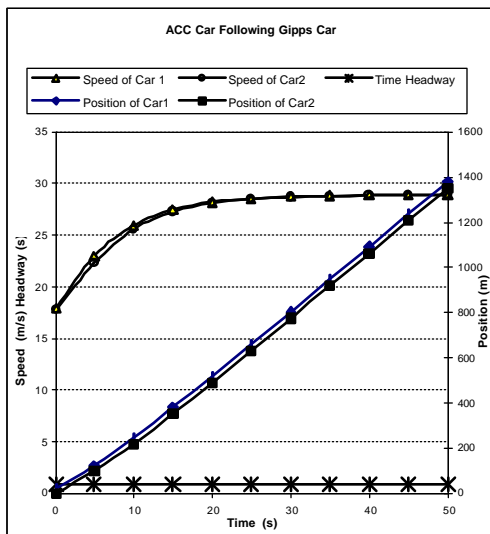
Figure 1. Flowchart of simulation Program



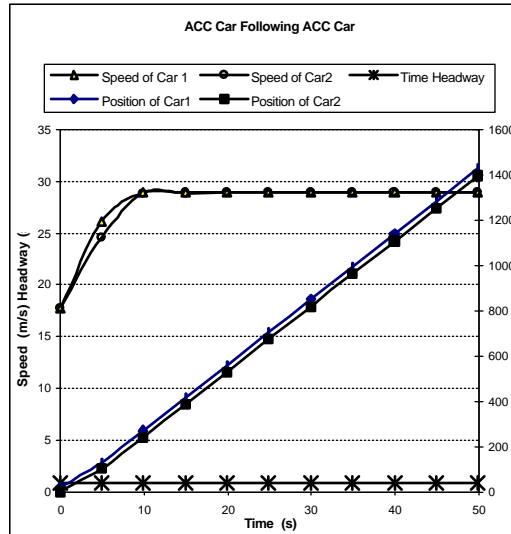
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(b)

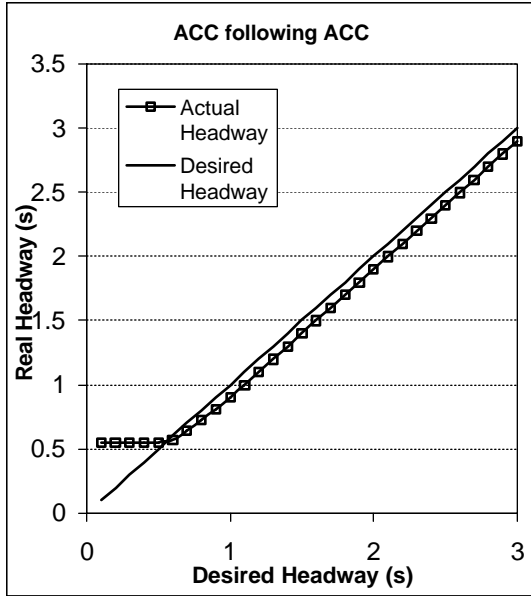


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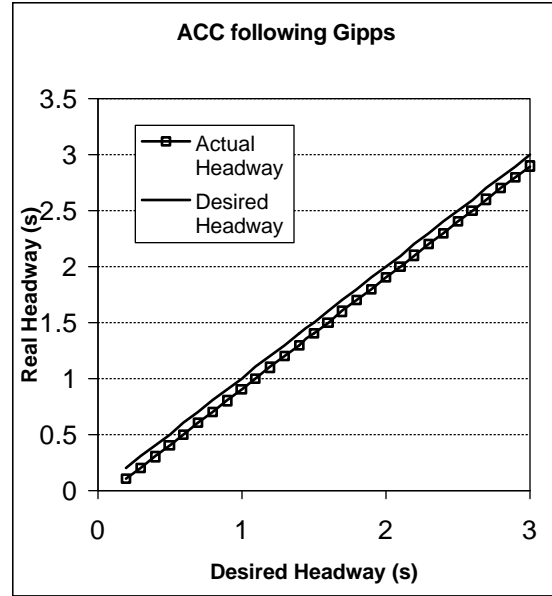


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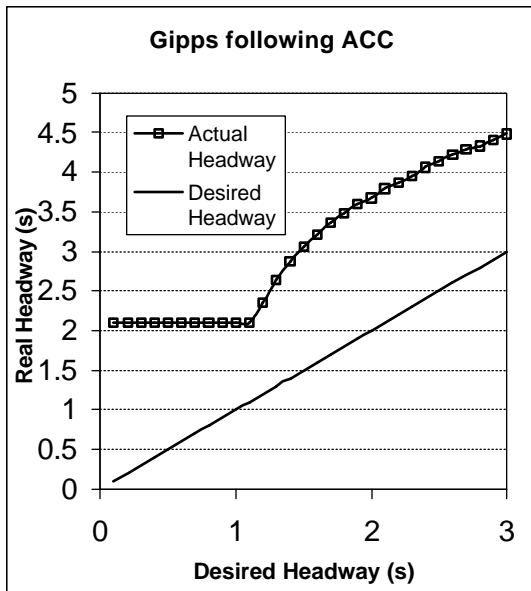
Figure 2. Single Vehicle's Following Behaviors



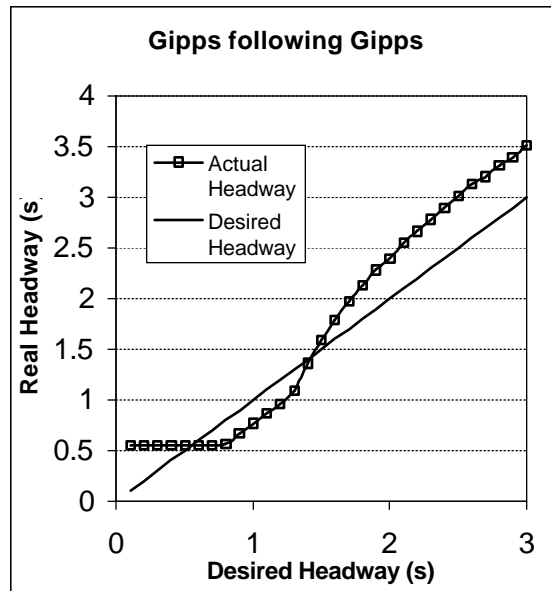
(a)



(b)



(c)



(d)

Figure 3. Headway Response Of Single Vehicle

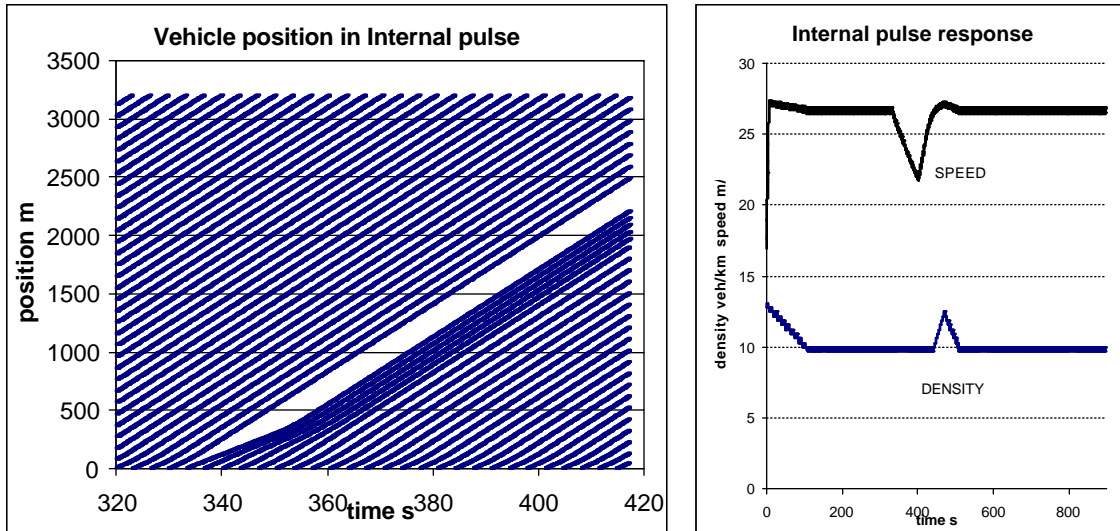


Figure 4. Vehicle Positions, Density and Speed Profiles in an Internal Pulse

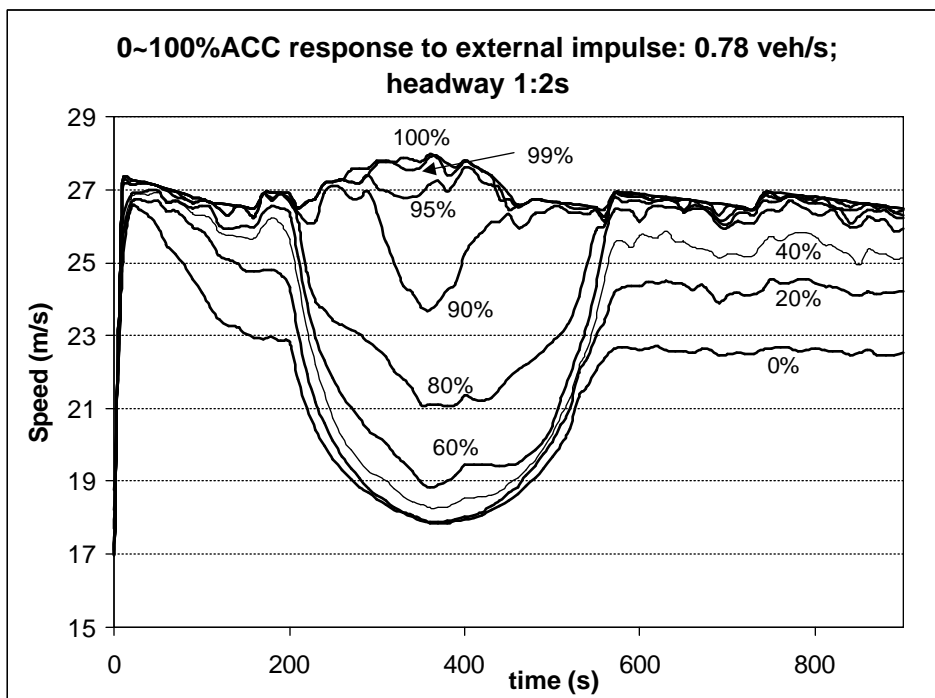


Figure 6. Speed Profiles under Different ACC Penetrations

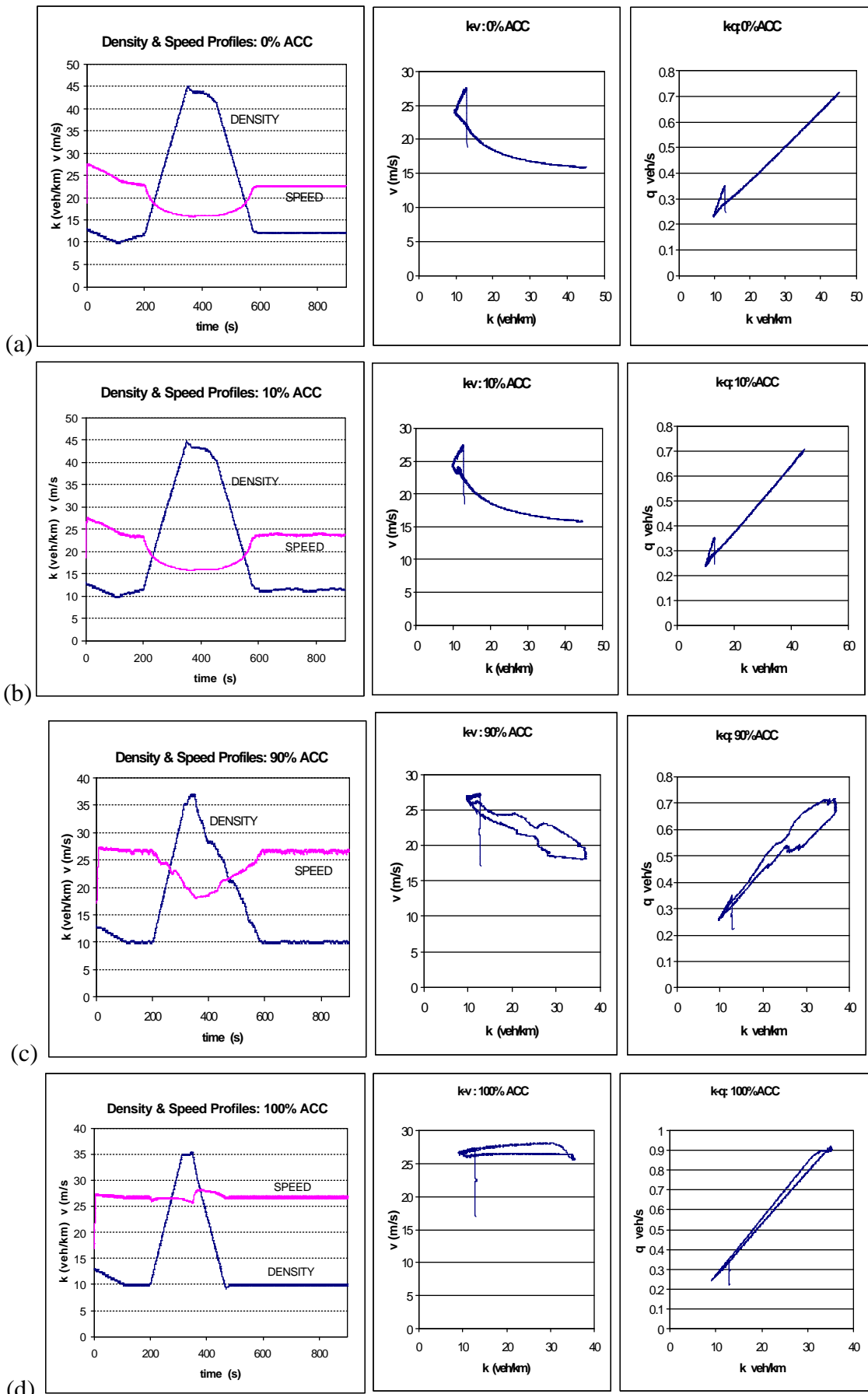


Figure 5. Response of Mixed System to External Impulse

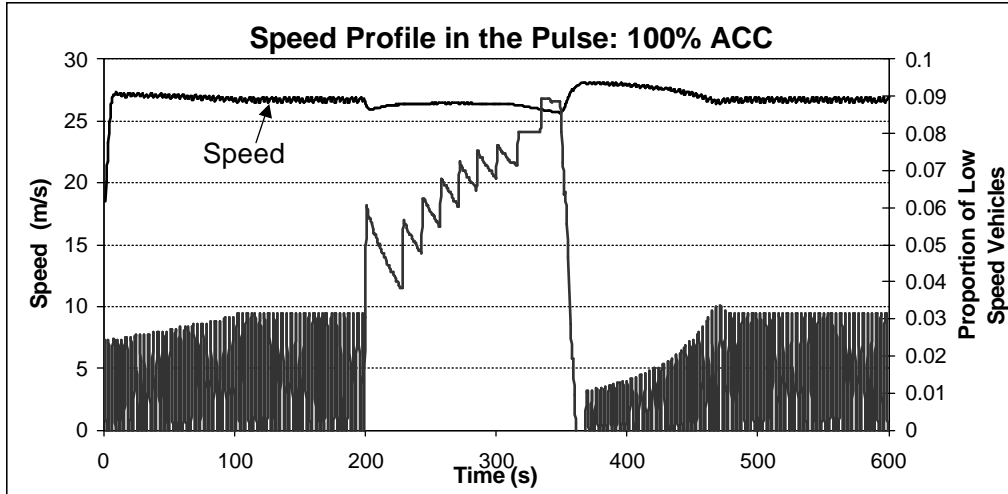
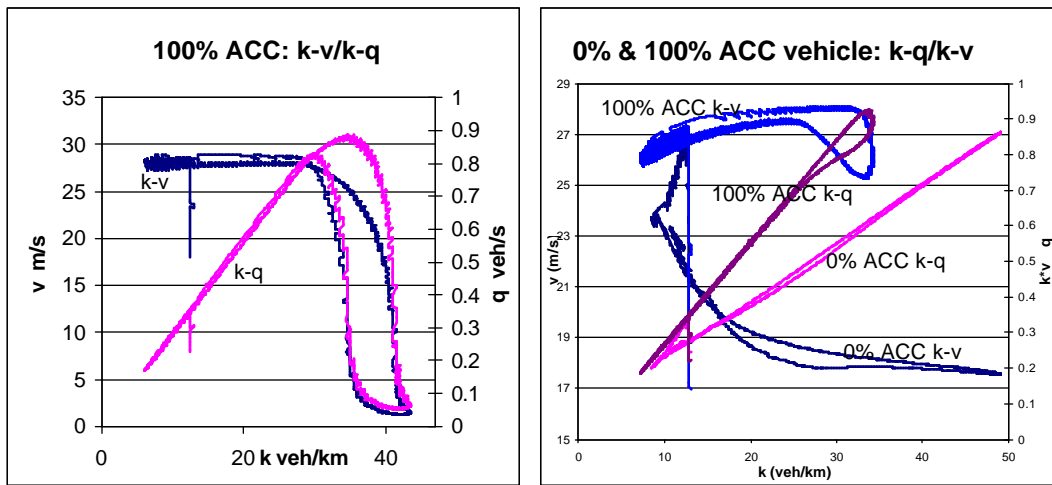


Figure 7.



(a) Beyond Capacity

(b) Under Capacity

Figure 8. k - q & k - v Relations of Dynamic Process

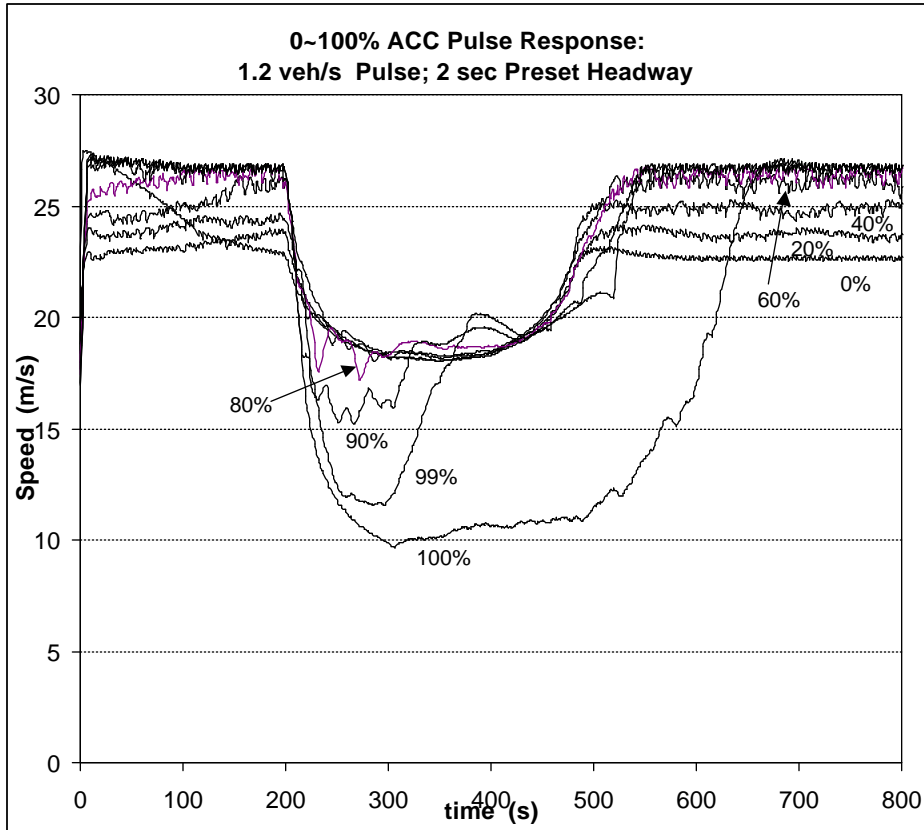


Figure 9. Speed Profiles under Different ACC Penetrations

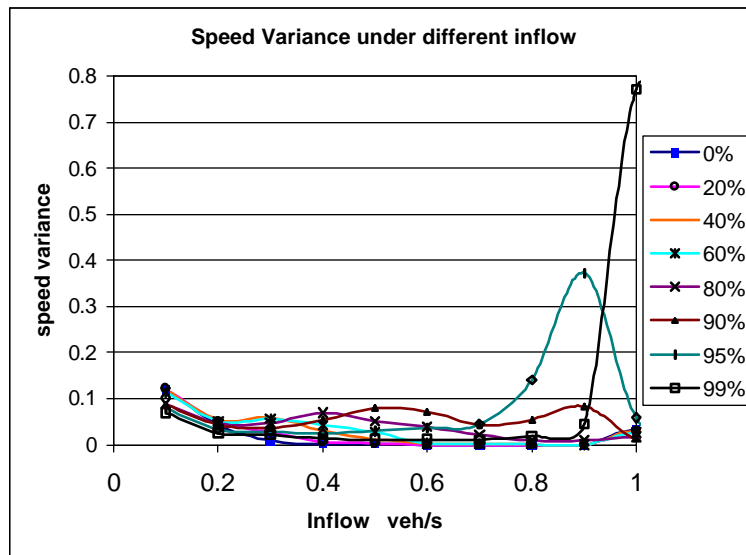


Figure 10. Speed Variance under Different Inflow and Different ACC Penetration