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GRADUATE SCHOOL

SIMULATION AND ANALYSIS OF

MIXED ADAPTIVE CRUISE CONTROL /

MANUAL TRAFFIC

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

Xi Zou

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

March 2001

ACKNOWLEDGEMENT

This thesis exists due to the wonderful support I have had throughout the last two year. I would like to thank the following for their contributions:

- Professor David M. Levinson, my advisor, for his invaluable support and the opportunities that he has presented me with.
- Professor Panos G. Michalopoulos and Professor Rajesh Rajamani, for direction and continued support.
- My family, comfort from China, my homeland. My father, Professor Mou-yan Zou, espicailly, for his encouragement and inspiration.
- My friends, Lei, Satya, Shantanu, Atif, Pavi, Seshu, Bhanu, Rama, Hong, Yao, Wei, Peter, Kasia for their support, suggestion and friendship.
- The Center for Transportation Studies and ITS Institute for their financial support.

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 thesis, measurement of traffic quality is discussed. A definition of traffic flow stability is proposed. 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 is 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 Headway (CTH) control ACC compared with human drivers.

This thesis addresses the impacts of Adaptive Cruise Control laws on the traffic flow. Simulation results of various mixed fleet scenarios under different ACC laws are presented. Explicit comparison of two ACC laws, Constant Time Headway and Variable Time Headway (VTH), are based on these results. It is found that VTH 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 than CTH.

Key words: Adaptive Cruise Control, Vehicle Highway Automation, Mixed Traffic Flow, Evaluation,

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1

INTRODUCTION

1.1 BACKGROUND

Since the 1960's, concerns about the motorway safety from public, government and automakers have brought along many passive safety features, such as lighting, seat belts and air bags, which significantly reduced the rate of crashes, injuries and mortalities. The fatality rate per hundred million VMT has been reduced from 5.5 to 1.7 (NHTSA, 2000). However, motor vehicle accidents are still major threats to people's life and possess. From technical point of view, it is very difficult to obtain further improvement solely based on current passive safety technologies.

The potential solution for this problem is the application of active safety technologies. Among them, collision warning system (CWS), collision avoidance system (CAS) and adaptive cruise control (ACC) are highlighted because of their effectiveness in reducing rear-end crashes. These techniques or their combination are capable of detecting objects ahead of vehicle and taking action to avoid accidents. CWS can provide visual and audio warning to the driver. CAS and ACC can actuate braking through Anti-lock Brake System or other actuators automatically. Because rear-end collisions are more than one third of fatal and injury collisions (NHTSA, 2000), people expect that these systems can dramatically diminish life and possess loss in motorway.

ACC system is the most widely used term for systems equipped with forward-looking laser or millimeter wave radar and are capable of automatically changing engine speed and/or applying brakes to achieve preset speed or inter-vehicle headway. Many other names of systems with similar function include:

- Intelligent Cruise Control
- Radar Cruise Control (Toyota)
- Collision Avoidance System
- Headway Control System
- Smart Cruise (Eaton Vorad)
- Autocruise (Autocruise)
- Preview Distance Control (Mitsubishi)
- Distronic (Daimler)
- Intelligent Highway Cruise Control (Honda).

Conventional cruise control (CCC) is an important feature for American drivers because they have more long-range freeway journeys than their Europe counterparts. But CCC cannot be used in the heavy traffic in urban area. ACC is developed to solve this problem. Besides the basic function of ACC to maintain the vehicle's preset speed, the system also maintains the inter-vehicle headway that is preset by drivers. Through the integration of advanced radar sensors, digital signal processor and longitudinal micro-controller, ACC can maintain preset headway by accelerating or decelerating vehicle according to traffic condition ahead. For instance, if a car cuts in ahead and the headway in terms of distance or time gap is reduced, ACC applies brake until the preset headway is restored. If the leading vehicle speeds up or moves out of the current lane, ACC accelerates the car until it catches up with another car or gets to the preset cruise speed.

Automakers have already begun to equip some makes of vehicles with ACC-like systems. Mitsubishi's Preview Distance Control system is the first distance control system in the world, which is mounted in its Diamante in 1995. (HIDO, 2001) The first ACC system is introduced by Toyota in its Progres sedan in 1998 (HIDO, 2001). Other automakers, such as Nissan (Hido, 2001), Jaguar (Jaguar, 2001), Lexus (Ivsource.net, 2000), Mercedes-Benz (ISA, 2001) and Honda (Hido, 2001) are also engaged in this direction. On the other hand, auto-electronics companies, such as TRW, Thomson-CSF (Tire One, 2001a), Delphi Delco (Delphi, 2001), Eaton Vorad (Eaton Vorad, 2001) and Visteon (Visteon, 2001), have also developed their ACC systems, hoping to obtain a share in a promising market which, as predicted by Tire One, will reach to $2 billion a year in the next ten years (Tier One, 2001b).

Furthermore, the current ACC system is not seen as the ultimate solution. For instance, ACC is combined with inter-vehicle communication, which yields Cooperative ACC (CACC), in California (Jones, 2001). It is hoped that this technique might reduce the time headway to as short as 0.5 seconds (Jones, 2001). By enhancing their radar system, Fuji Ten wants to develop a stop-and-go ACC which can work in congested traffic (Jones, 2001). In US Department of Transportation (DOT) and GM's joint project, they want to develop a system combining ACC with collision warning system (FHWA, 1999).

Currently, the claims on the aims of developing ACC system differ among automakers and auto-electronics producer. While some of them remain in the conventional applications of cruise control: reducing fatigue, providing alert and enhancing comfort, others are looking for the potential benefit in passenger safety and road capacity. On the other hand, safety and many other related issues must be considered before the implementation of ACC systems, such as:

(1) The impacts of ACC on driver behavior and their ability to respond in emergency situations still need investigation. Drivers may choose the headway ranging from 1.0 second to 2.0 second in heavy traffic (Ayres et al., 2001). On the other hand, ACC must set headways below 1.2 seconds to avoid reducing road capacity (DIATS 2001). By all

means, the headway is below 3 seconds that is recommended by some administrations (for instance, California Driving Manual 2001) for safe driving. So a problem lies in choosing the ACC headway: should driver obey recommendations that result in capacity reduction? If they obey recommendations, who owns the liability in the case of accidents? The answer is not easy to obtain but must be worked out by government agency and automakers.

(2) Another challenge in front of ACC producers is how much control the system should have over the vehicle. Conventional ACC will at most serve as a warning system in serious situations because most don't see ACC as a collision avoidance system that would apply the brakes aggressively. The problems include to what degree should ACC hand over control of the car to the driver and when should ACC alert the driver that instant intervention is needed.

(3) Though ACC is designed for heavy traffic driving in urban areas, congestion can still create challenges. For instance, if a driver presets too much space or headway, another driver with less desired headway might cut in. ACC, reasonably, would slow down to restore the headway. That might allow another car to cut in, and again the car would have to slow down to keep the preset headway. Frustrated drivers might turn off the ACC because of frequent speed changes and loss of priority.

(4) Even in light traffic, frequent lane-changing may raise problems. ACC system should be capable of picking up right leading vehicle in its current lane while its radar can track dozen of objectives at a time. The lane-changing behavior of human drivers will not be duplicated in this case. Normally, to take advantage of gap in the target lane, drivers will accelerate and steer synchronously. In this process, the headway between this car and the

leading vehicle in the current lane may be smaller than that in the normal driving condition. An activated ACC system will not tolerate this “unsafe” state. The car will not accelerate unless its headway in the newly-entered lane is larger than the preset value. That means it need bigger gap in the target lane to perform lane-changing. The expected scenario, in which ACC is responsible for longitudinal control and the driver for latitudinal control, may not be easily implemented.

(5) Furthermore, ACC system should be capable of distinguishing lane-changing with curve driving status and thus picking up the leading vehicle correctly. A practical problem is that ACC system may underestimate the headway in the curve, decelerate unnecessarily and frequently, and thus reduce comfort and make traffic less stable.

1.2 LITERATURE REVIEW

DESIGN CONSIDERATIONS OF ADAPTIVE CRUISE CONTROL

While vehicle manufacturers hope that ACC systems will improve the driver’s comfort and safety, 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). 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. For instance, Tier One forecasts that by 2010, 20 percent of cars will be equipped with either ACC-Collision Warning or other headway control systems (Tier One, 2001b). This mixed control scenario raises complex capacity and safety issues on traffic flow that we must probe before ACC becomes reality. The impacts of the deployment of ACC on the traffic flow pattern and its control must be taken into consideration in the very early stage of ACC design. Up to now, important design considerations of ACC systems largely include: (1) Maintains safe distance between vehicles: the system may fully control the vehicle, and it must guarantee that the vehicle will not enter an unsafe state as a result of the control; (2) Characteristics of real-time response: the respond time of the vehicle to control inputs must be short; (3) All-weather capability: Performs well in poor visibility conditions and should not be adversely affected by poor weather conditions; (4) Performs well during road turns, bumps and slopes; (5) Simplicity of use: A driver with no prior experience can use it correctly.

Patterson (1998) studied ACC's impacts on capacity and safety. His thesis compared ACC with conventional cruise control and manual driving in both macroscopic and microscopic level. In macroscopic level, it is found that ACC was used more in similar trips and the number of brake interventions in ACC vehicles is larger than that in CCC vehicles. In the microscopic level, it is found that manual driving results in larger headway. But ACC and CCC have similar speed-headway profiles.

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 divergence of the ratio of vehicle distance to desired vehicle distance and the relative speed of two vehicles. Holve et al. (1995a) suggested that ACC system has to meet the expectations of the human driver to a certain degree. They proposed an adaptive fuzzy logic controller that is flexible in different driving situations and comprehensible for the driver. Holve et al. (1995b) also proposed a scheme to generate fuzzy rules of ACC controller, in which the driver is a component of the ACC control loop. Their Fuzzy-ACC has been tested in normal road traffic. 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 of the ACC vehicle is related to the vehicle mass, the gap headway, the rate of change of gap headway and the velocity of the equipped vehicle. Their results showed that ACC could reduce the variation of acceleration compared to manual driving (Marsden et al., 2001). It should be noted that the authors also pointed out the limitations of microscopic simulation in modeling the impacts of ACC because of the lack of knowledge of the behavior and interaction between the driver and the ACC system in different traffic conditions (Marsden et al., 2001).

Ioannou et al. (1994) proposed their ACC scheme for constant time vehicle following. Their results showed that the scheme could maintain a steady state of inter-vehicle spacing without reducing the driver comfort.

STUDY IN THE ASPECT OF TRAFFIC FLOW

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). Liang and Peng (1999) presented a two-level ACC synthesis method which calculates desired acceleration rate and controls vehicle to achieve the desired rate accurately. They suggested that their method can guarantee string stability and yield minimum impact on vehicles nearby. Furthermore, they (Liang and Peng, 2000) suggested a framework to analyze string stability and defined a margin index to give a quantitative measurement of ACC designs.

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 is 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. Bose and Ioannou (2001) reported their studies on the mixed traffic of ICC vehicles and manual driven vehicles. Their results showed that 10% presence of ICC vehicles help to smooth traffic flow in the case of rapid acceleration of leading vehicle, which results in less fuel consumption and pollution levels than pure manual driven traffic.

Sponsored by the National Highway Traffic Safety Administration (NHTSA), an ACC system evaluation project (Koziol et al. 1999) was implemented by the University of Michigan Transportation Research Institute from July 1996 to September 1997. Based on data obtained from the experiments, the Volpe National Transportation Systems Center (Volpe Center) investigated ACC's impacts. They concluded that deployment of ACC results in safer driving (Koziol et al. 1999).

Fancher et al. (1998) reported the ICC Field Operational Test of NHTSA and UMTRI. They concentrated on the safety and comfort issues of ICC (ACC) system. They found that ACC is very attractive to most drivers and is used in many traffic conditions (Fancher et al., 1998). On the other hand, they found some issues indicate potential impacts on safety and traffic; the importance of human-centered design is also highlighted (Fancher et al., 1998). In the aspect of assessing impacts on traffic flow, they suggested that the current results are not enough for analysis (Fancher et al., 1998).

Swaroop and Huandra (1999) studied the design problem of ACC algorithm. Based on analysis and numerical simulation, they demonstrated that a good ACC spacing policy must satisfy the condition that the slope of the corresponding fundamental traffic characteristics is always positive.

VanderWerf et al. (2001) studied the impacts of autonomous ACC (AACC) and cooperative ACC (CACC) on traffic based on their microscopic simulation. They found that AACC have very small impact on highway capacity. The capacity gain from 0% to 20% AAC penetration is greater than that from 20% to 40%. And there is no capacity increase with more AACC penetration (VanderWerf et al., 2001). Cooperative ACC, on the other hand, can potentially increase capacity quadratically along with CACC penetration (VanderWerf et al., 2001).

All of this research provided the estimates of impacts of ACC in some specified situations. Their results are meaningful for the traffic operators to outline the potential impacts of ACC system. Our research will begin with the some simplified scenarios 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.

1.3 CONTRIBUTION OF THIS THESIS

In this thesis, I will discuss methodology and criteria that can be used to evaluate the impacts of ACC algorithms 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 or variable time headway while following. The newly-developed variable time headway control algorithm is implemented in simulation and compared with constant time headway algorithm. 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 chapter 2, the evaluation issues of traffic flow, such as stability, robustness and safety, are discussed. Chapter 2 also describes the mixed traffic scenario that is investigated and the simulation program. Chapter 3 to Chapter 5 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. Chapter 3 presents the simulation results of traffic flow mixed by constant time headway ACC and manual driven cars. Chapter 4 compares the performance of variable time headway and constant time headway ACC. Chapter 5 shows the simulation result in which headways of ACC and manual driven vehicles are randomly distributed. Comparisons are made to show the impacts of random factors. Some concluding remarks in Chapter 6 complete the thesis.

2

EVALUATION OF ADAPTIVE CRUISE CONTROL

2.1 INTRODUTION

The evaluation of the impacts of ACC on traffic flow is a based on measurements of traffic quality. Traffic operators want (1) a high capacity of traffic flow in the current infrastructure; (2) stable traffic flow in the cases of high demand and incidents and (3) guaranteed safety for each driver.

High capacity can only be obtained when the average time headway is reduced while keeping the same speed. That means vehicles are closer to each other in the same speeds. ACC provides a very short response and may take the place of the driver in longitudinal control. However, this improvement will raise a safety problem if the response time of the driver-vehicle system cannot be reduced in the same scale. The tradeoff point in terms of capacity and safety can be chosen based on safety requirement, which is determined by the mechanics of vehicle and infrastructure, such as vehicle dynamics, road surface friction, efficiency of Anti-lock Brake System and even weather.

Smooth traffic is also desired by users and operators because it means less travel time and less potential incidents. The problem is how to reduce congestion and make traffic more stable. A clear definition of traffic flow stability is still unavailable in previous studies because of the nonlinear, dynamic and stochastic nature of traffic and the fuzzy aim of term defining. Stability, which is traditionally used to describe the internal characteristic of system to maintain a bounded movement, is different from robustness, which is used to evaluate the external characteristic of system: the insensitivity of a system to input variation. In traffic studies, these two terms are often blurred and treated as the same quantity. But distinguishing these two quantities are significant in the case that one considers the upstream traffic as the input of downstream traffic in traffic flow operation. Unfortunately, up to now, there are no explicit qualitative definitions of them. A promising approach to investigate these characteristics is the study of traffic congestion in which many reasons cause oscillations in speed, density and flow rate. Traffic congestion is such a complex phenomenon that none of up-to-date theories, such as car-following model (Rothery 2000), queuing theory (Newell. 1982), kinetic theory (Prigogine And Herman 1971), cellular automata (Nagel and Shreckenberg 1992), higher-order model (Kuhne and Michalopoulos 2001) and kinetic wave theory (Lighthill and Whitham 1955), can soundly describe it, though everyone have to experience it in daily life.

2.2 MEASUREMENTS OF TRAFFIC QUALITY

TRAFFIC FLOW STABILITY

Many investigations have been conducted to study the stability issues of traffic flow. But most of them are concentrated on string stability. **String stability** is stability with respect to inter-vehicular spacing. It ensures the position and speed of each vehicle in a string change within small boundaries of error, and disturbances in vehicle speeds do not be amplified when they are propagated upstream in traffic. Normally, no vehicle enters or leaves the string in the study of string stability. It should be noted that guaranteeing string stability doesn't mean guaranteeing flow stability. String stability might achieve that the space between vehicles in the string remain the same constant, but can not keep the speed of vehicles in the string from decreasing to a level that blocks the string in a motorway section and thus causes an instable state of traffic flow.

In a macroscopic scale, traffic flow is the aggregation of strings and single vehicles in many sections of motorway. Traffic flow stability deals with the evolution of aggregate velocity and density in response to change in the flow rate. So vehicles enter and leave specified traffic in the study of flow stability. Darbha and Rajagopal (1999) proposed that, "Traffic flow stability can be guaranteed only if the velocity and density solutions of the coupled set of equations is stable, i.e., only if stability with respect to automatic vehicle following and stability with respect to density evolution is guaranteed." Their definition is in the senses of Lyapunov. A formal definition of Lyapunov stability is (Murray et al. 1994):

The equilibrium point x=0 of* $\dot{x} = f(x,t)$ *is stable at* $t=t_0$ *if for any* $\epsilon > 0$ *there exists a* $\delta(t_0, \epsilon)>0$ *such that:*

$$\|x(t_0)\| < \delta \quad \Rightarrow \quad \|x(t)\| < \varepsilon, \quad \forall t > t_0 \tag{1}$$

Furthermore, the **asymptotic stability** is defined as (Murray et al. 1994):

The equilibrium point x=0 of* $\dot{x} = f(x,t)$ *is asymptotic stable at* $t = t_0$ *if*

1. *x*=0 is stable, and*
2. *x*=0 is locally attractive; i.e. there exists* $\delta(t_0)$ *such that*

$$\|x(t_0)\| < \delta \quad \Rightarrow \quad \lim_{t\to\infty} x(t) = 0 \tag{2}$$

Here a point x* is an equilibrium point of $\dot{x} = f(x,t)$ where $f(x^*,t) \equiv 0$.

Darbha and Rajagopal define **Traffic Flow Stability** for automated vehicle traffic as:

Let $v_0(x,t)$, $k_0(x,t)$ *denote the nominal state of traffic. Let* $v_p(x,t)$, $k_p(x,t)$ *be the speed and density perturbations to the traffic, consistent with the boundary conditions and are such that* $v_p(x,t) \equiv 0$, $k_p(x,t) \equiv 0$ $\forall x \geq x_u$. *The traffic flow is stable, if*

1. given $\varepsilon > 0$, *there exists a* $\delta > 0$ *such that*

$$\sup_{x \leq x_u} \{ |v_p(x,0)| |k_p(x,0)| \} < \delta \quad \Rightarrow \quad \sup_{t \geq 0} \sup_{x \leq x_u} \{ |v_p(x,t)| |k_p(x,t)| \} < \varepsilon \tag{3}$$

and

2. $$\lim_{t \to \infty} \sup_{x \leq x_u} \{ |v_p(x,t)| |k_p(x,t)| \} = 0 \tag{4}$$

Where sup(.) is the abbreviation for supremum or least upper bound, which means, for a given set of number S, the smallest element of a set U as the upper bounds of S. This definition of stability can be described in Figure 1. (v_0, k_0) is a steady state of traffic. Here the traffic flow is defined to be stable when the disturbance (v_p, k_p) does not exceed a boundary if its initial value is within a limit, and, in the end, the disturbance becomes zero. As shown in the enlarged figure in Figure 1, if the initial state is within the boundary (the triangle point), it goes to the equilibrium point (v_0, k_0) in the end; but if the initial state is beyond the boundary (the rectangle point), it does not converge to the equilibrium point but goes to other indefinite states.

This definition is very strong in that the disturbance must be eliminated over time by its own movement. In real-world traffic, disturbances or unstable traffic usually are eliminated because of light demand inflows which happen from time to time. On the other hand, it's also a loose definition because it doesn't present the traffic state change from free flow to congestion in which the change of the "nominal state of traffic" itself is the source of traffic flow instability. Thus, a Lyapunov stability definition in terms of speed-density relation may not work well in describing traffic stability.

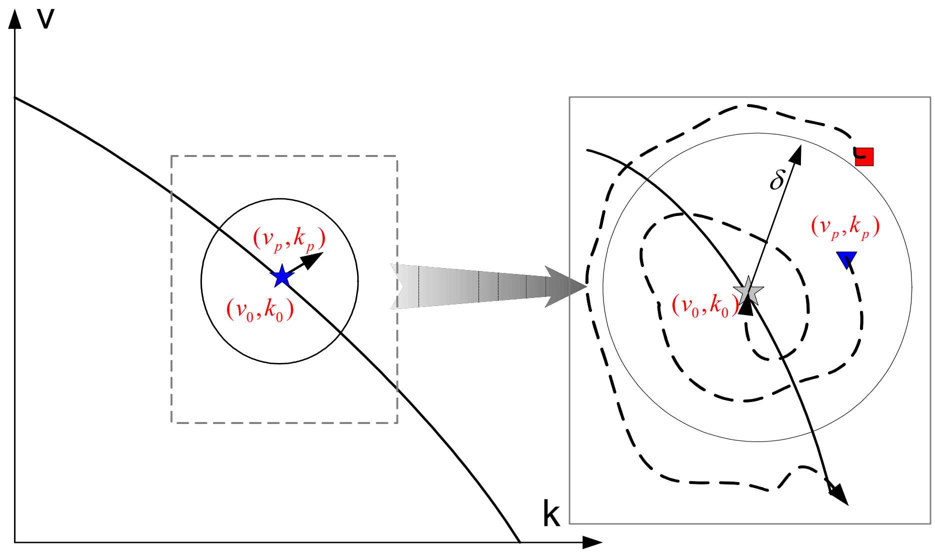


Figure 1. Stability in Term of Speed-Density Relation

In author's paper (Zou and Levinson 2001), a new criterion function of the relation between density and flow rate is proposed to detect potential traffic breakdown.

(1) The convolution is defined as:

$$C(f,h)=\int_{-\infty}^{\infty} f(t)h(u-t)du \tag{5}$$

The moving-average of density is defined as:

$$\begin{cases} k_{low}=C(k(t),P(t)) \\ P(t)=\begin{cases} 1 & t_2<t<t_1 \\ 0 & t<t_2, t>t_1 \end{cases} \end{cases} \tag{6}$$

(2) The filtered high frequency components $k^*(t)$ are restored by subtracting low frequency components from the original signal, which is defined as **Density Dynamics**:

$$k^*(t)=k(t)-k_{low}(t) \tag{7}$$

(3) **Cross-Correlation** is always used to detect the diversity of measurements:

$$\langle f,h\rangle = \int_{-\infty}^{\infty} f(t)h(u+t)du \tag{8}$$

We conduct a template cross-correlation calculation of density dynamics and flow rate:

$$corr(k^*,q) = \max\langle \overline{k}^* \cdot \overline{q} \rangle \tag{10}$$

where $\overline{k}^*$ and $\overline{q}$ are templates of k^* and q, respectively, move simultaneously. Template means a consecutive portion of data in a series. The new criterion function is defined as:

$$z(t) = \frac{d}{dt}(corr(k^*,q)) \tag{11}$$

The computation results based on real world traffic data justified the effectiveness of this function. It's shown that there is a traffic breakdown only when $z(t) = \frac{d}{dt}(corr(k^*,q)) > z_0$, where z_0 could be a threshold obtained from experience. If the changing rate of the cross-correlation exceeds the threshold, the transition is unreturnable. Another important property is that the criterion function has a singular peak in the onset of the phase transition. These results indicate that the criterion function might be a mathematical description of phase transition in traffic flow which presents the traffic flow moving from stable to instable states.

In deriving the criterion function, we find concentrations of traffic states in both free flow and congested traffic by means of moving–average computation, as shown in Figure 2. This intuitively provides support of previous studies that suggest distinct phases in traffic flow. Also, the transitions that happened between relatively stable phases represent cases when the system loses or regains stability. Thus the transient condition of traffic flow we obtained sheds light on the conceptions of traffic stability and robustness.

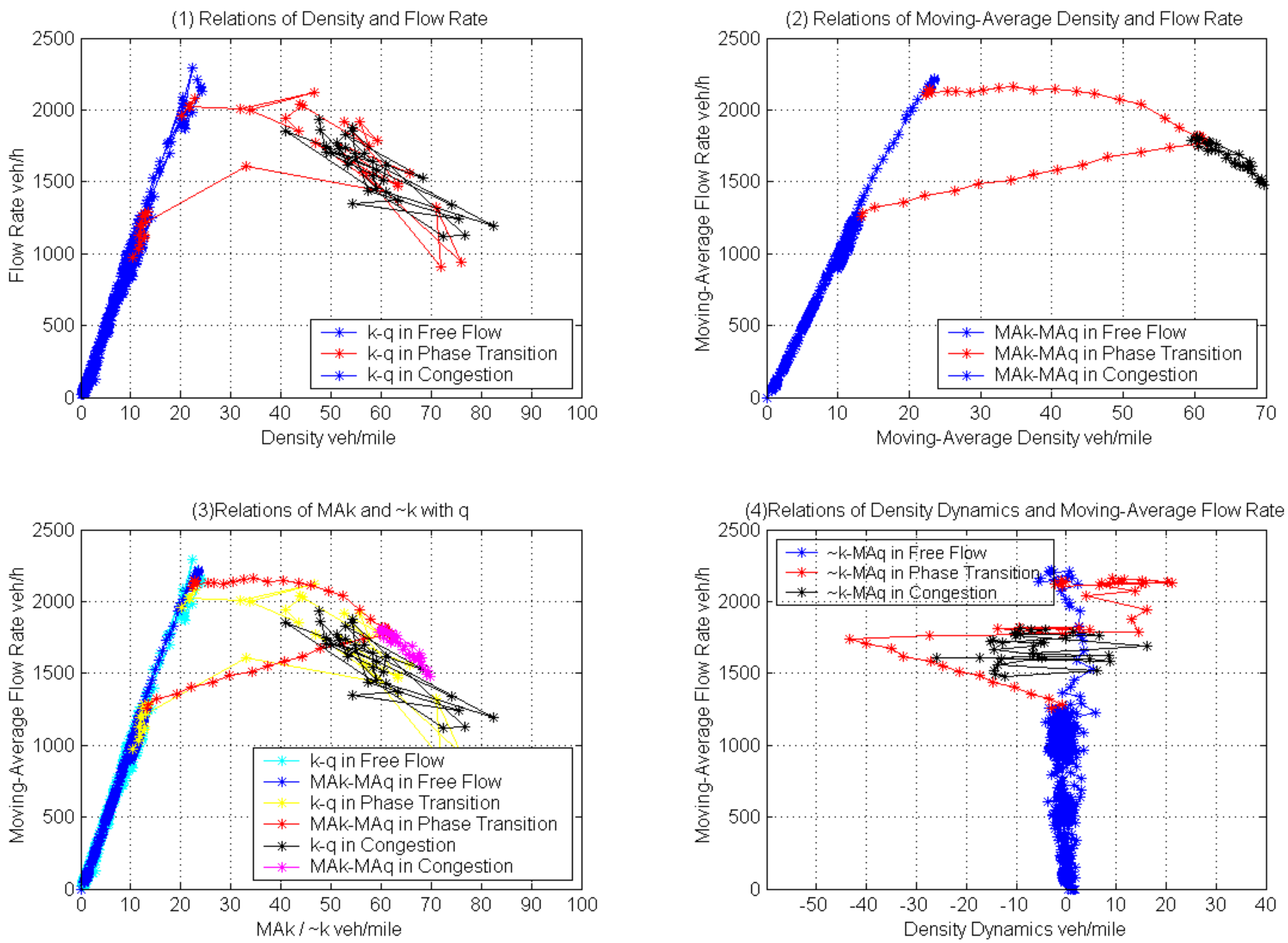


Figure 2 (~*k* is k^* in these graphs; MA means moving-average)

If the traffic transferring from free flow to congestion is considered as an unstable state, we can provide stability and instability criterion as:

Stability Criterion

The traffic flow will remain stable if the changing rate of the cross-correlation between flow rate and density dynamics is always within a boundary, i.e., $z(t) = \frac{d}{dt}(corr(k^*, q)) < z_0$.

Instability Criterion

The traffic flow will be unstable if the changing rate of the cross-correlation between flow rate and density dynamics exceed a boundary, i.e., $z(t) = \frac{d}{dt}(corr(k^*, q)) > z_0$.

Figure 3 illustrates the basic movement of traffic flow in losing and regaining stability. Our study shows that: if the initial state is within the boundary of stable states cluster, and if the state transition satisfies the stability criterion, the traffic will remain stable. Otherwise, traffic will loss stability and goes to congestion states. This is a kind of Lyapunov stability. By Lyapunov stability, we mean that the state disturbances, that satisfy the boundary conditions, remain bounded.

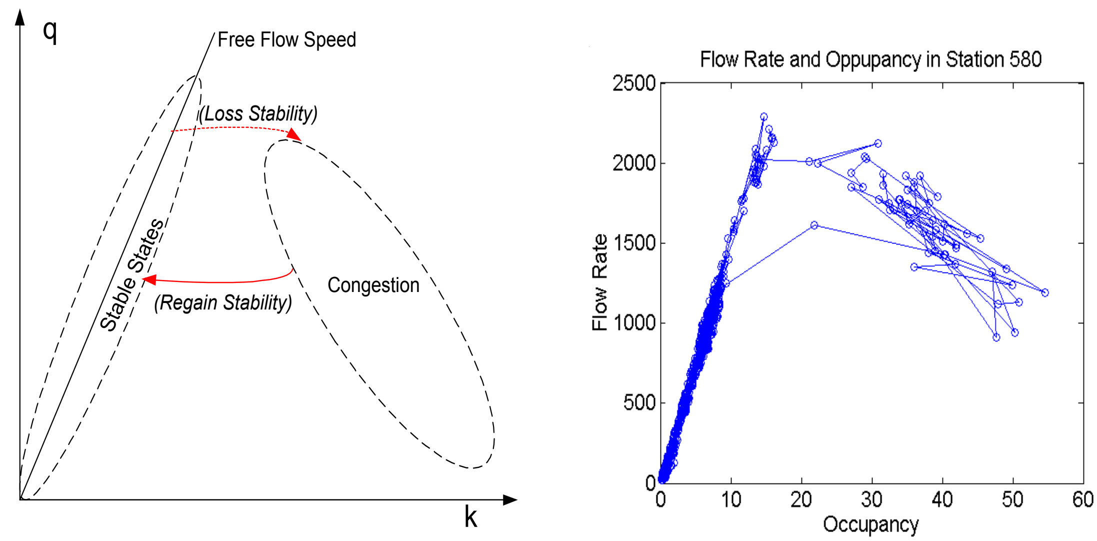


Figure 3. Stability Change of Traffic Flow

Robustness of Traffic Flow can also be defined in this way. 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. Our results show that if the disturbance is within the boundary, the phase of traffic flow will not change. So the measurement of robustness of traffic flow is the boundary of the changing rate of the cross-correlation between flow rate and density dynamics. As one can see in Figure 4, the traffic experienced a disturbance at some time and run away from the free flow curve, but it didn't result in a congestion but went back to stable traffic (the circled portion). At another time, the boundary was exceeded and jam presented.

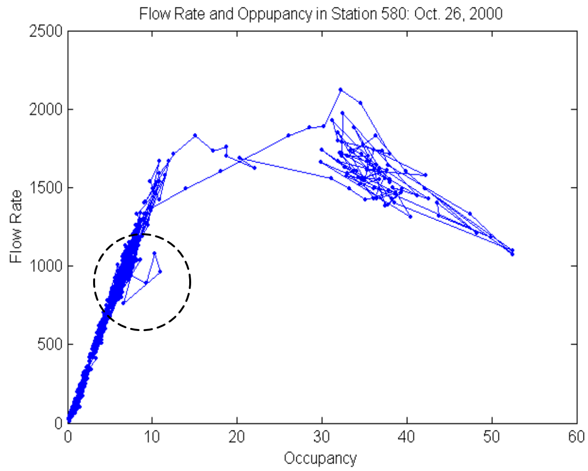


Figure 4.

Though this criterion function cannot be easily applied to the evaluation of ACC, it at least indicates that: the density dynamics should not be too large in the case of high flow rate. Otherwise, traffic will be unstable. From the microscopic point of view, it means that the response time of vehicles should not be too small. It's a reasonable induction in that drivers responses to the density change ahead. If the change is drastic, drivers will respond more seriously, which causes big disturbances that affect upstream traffic adversely. The ACC designers should consider this influence of ACC's behavior in mixed traffic.

SAFETY

Traffic safety is a problem related with headway, response time of driver/automated system, vehicle mechanical delay and road surface condition. Normally safety can be guaranteed if the headway is greater than the summation of response time and delays.

Normally, the design of ACC algorithms is headway control design. While the headway control can be achieved effectively, there are still some practical problems to be solved. ACC headway design must consider all these factors. Such as:

(1) Who should be responsible for emergency braking? The maximum of deceleration of current ACC system is not enough for it. If it is the driver's responsibility, when should the driver be alerted? That is a liability problem. Ideal solution might an ACC system combined with collision warning/avoiding system. In the latter one, ACC system is connected to ABS to apply braking commands.

(2) Should ACC change headway in the cases of special weather condition such as in icy, sleeting and rainy days? The preset headway in slippery surface should be longer than those in dry surface in the same speeds. Should the driver be responsible for identifying the environment changes and changing the preset headway? How much should the driver change? The ACC designer must provide guidance for these situations.

(3) Should the ACC system provide headway options according to driver's response capability? Should it determine the lower headway limit for driver with longer response time? How is the liability if the driver uses the least headway? ACC designers may take conservative values of preset headway to avoid risks, but the efficiency of traffic might deteriorate. On the other hand, the system might test the response time of driver by recording their behavior to imminent vehicles approaching.

2.3 MICROSCOPIC SIMULATION SYSTEM CONFIGURATION

The above discussion on traffic flow stability and safety is meaningful for the evaluation of ACC algorithms in that it provides some qualitative and quantitative measurements. But the evaluation of the impacts of ACC cannot be easily solved analytically, because the mixed traffic flow is the aggregation of vehicles with different control behavior and its properties cannot be obtained from the uniform mathematical model or differential equations. So we use simulation tools to observe traffic behavior and summarize ACC's impacts on the capacity, stability and safety of traffic before we get breakthrough in the theoretical analysis.

SYSTEM CONFIGURATION: 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. Although a number of driving simulator studies have been undertaken, these have 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). Nevertheless, 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 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 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 is responsible for all driving functions as in a manually driven vehicle except for the longitudinal control. 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.

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 will 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.

DYNAMIC MODELS OF THE COMPONENTS OF MIXED TRAFFIC

The main dynamic models used in the simulation are the vehicle dynamics, the ACC algorithm and the car-following model.

Vehicle Dynamics

The vehicle dynamics is simplified to a third-order differential equation:

$$\dddot{x}_i = \frac{1}{\tau}(\ddot{x}_{ides} - \ddot{x}_i) \tag{12}$$

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.

Adaptive Cruise Control Policy

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

$$\begin{cases} \ddot{x}_{ides} = -k_1\varepsilon_i - k_2\dot{\varepsilon}_i \\ \varepsilon_i = x_i - x_{i-1} + L \end{cases} \tag{13}$$

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

$$\begin{cases} \ddot{x}_{ides} = -\frac{1}{h}\left(\dot{\varepsilon}_i + \lambda\delta_i\right) \\ \delta_i = x_i - x_{i-1} + L + h\dot{x}_i \end{cases} \tag{14}$$

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 thesis, we use CTH control law as the primary one to test the impacts of ACC on the traffic flow.

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:

$$\begin{cases} \ddot{x}_{ides} = -\rho_m \left(v_f - \dot{x}_i \right) \left(1 - \dfrac{\dot{x}_i}{v_f} \right) \left(\dot{\varepsilon}_i + b\,\ddot{\varepsilon}_i + \lambda \delta_i \right) \\ \delta_i = \varepsilon_i + \dfrac{1}{\rho_m \left(1 - \dfrac{\dot{x}_i}{v_f} \right)} + b\,\dot{\varepsilon}_i \end{cases} \tag{15}$$

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 determine the how much the relative velocity contributes to the desired spacing.

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:

$$V_a(n,t+T) = V(n,t) + 2.5a(n)T\left(1 - \frac{V(n,t)}{V^*(n)}\right)\sqrt{0.025 + \frac{V(n,t)}{V^*(n)}} \qquad (16)$$

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:

$$V_b(n,t+T) = d(n)T + \sqrt{d(n)^2T^2 - d(n)\left[2\{x(n-1,t) - s(n-1,t) - x(n,t)\} - V(n,t)T - \frac{V(n-1,t)^2}{d'(n-1)}\right]} \qquad (17)$$

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:

$$V(n,t+T) = \min\{V_a(n,t+T), V_b(n,t+T)\} \qquad (18)$$

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

$$V(n,t+T)=x(n,t)+V(n,t+T)T \tag{19}$$

GENERATION OF TRAFFIC

As we have mentioned before, traffic generation complies with given traffic demand profiles. Normally, we use a 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 demand profile employed for the study was chosen to result in an overloading of road capacity during the middle 150 seconds (from 200 to 350 second) of the simulation. The other issue is to control the proportion of ACC vehicles. In our simulation, ACC vehicles are in traffic flow following a uniform distribution.

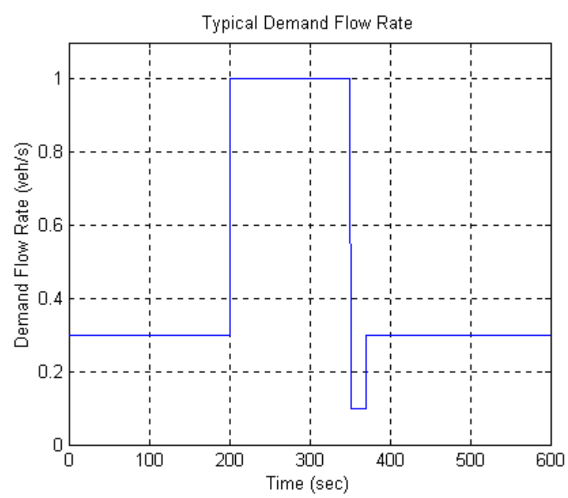


Figure 5. Typical Traffic Demand Profile

2.4 TRAFFIC SIMULATION PROGRAM

A microscopic simulation program is developed in C++. The flowchart of the program is shown in Figure 6. 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, which is the response time of ACC equipped vehicle. 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 determines 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 and Table 2.

Table. 1

System Configuration	
Road length	3212 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)
Parameters of operation	
Sample time (calculation cycle)	0.1 second
Simulation time duration	600 ~900 seconds

Table 2.

Parameters of ACC Algorithms	
Constant Time Headway	
λ	0.2
Time Headway	1.0~1.2 seconds
Variable Time Headway	
Free Flow Speed	31.78 m/s (71.5 mph)
λ	0.2

Parameters of Gipps' Model	
Desired Speed	28.9 m/s (65 mph)
Maximum Acceleration	1.7 m/s^2
Maximum Deceleration	-3.4 m/s^2
Time Headway	2 seconds

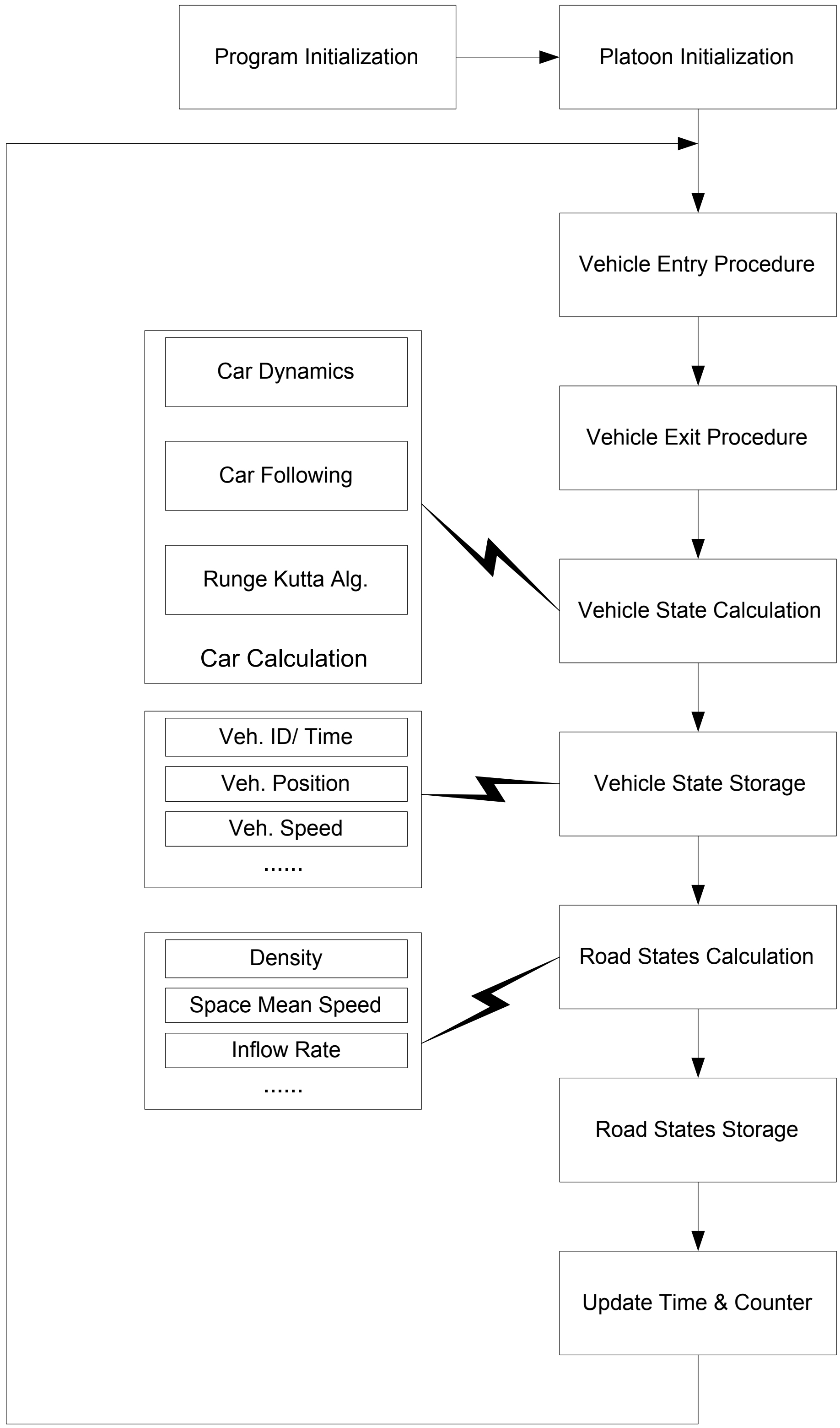


Figure 6 Flowchart of simulation Program

3

SIMULATION OF CONSTANT TIME HEADWAY AND MANUAL DRIVEN CARS

3.1 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 7. In these simulations, the preset time headway of ACC vehicle is 1 second, while that of 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 is shown that ACC vehicles will have a quicker response and thus smaller transient time than manual driven vehicles. So in these scenarios, Gipps' vehicles cannot catch the leading vehicles because the leading vehicles are free to accelerate. In contradiction, ACC vehicles can always maintain the constant time-gap. This result highlights an important advantage of ACC compared to manual vehicles: small time headway is more easily achieved by ACC vehicles; thus ACC vehicles generate capacity.

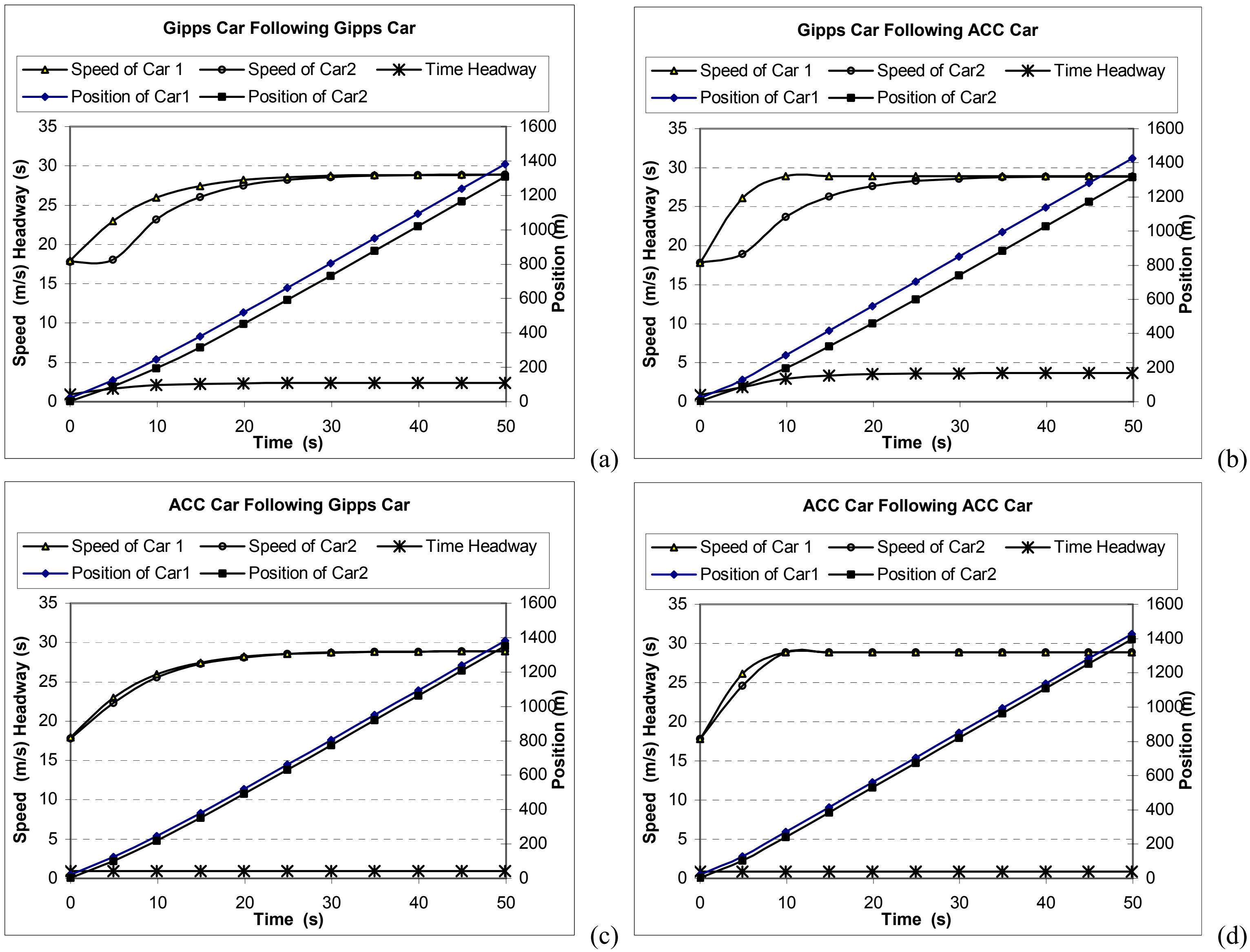


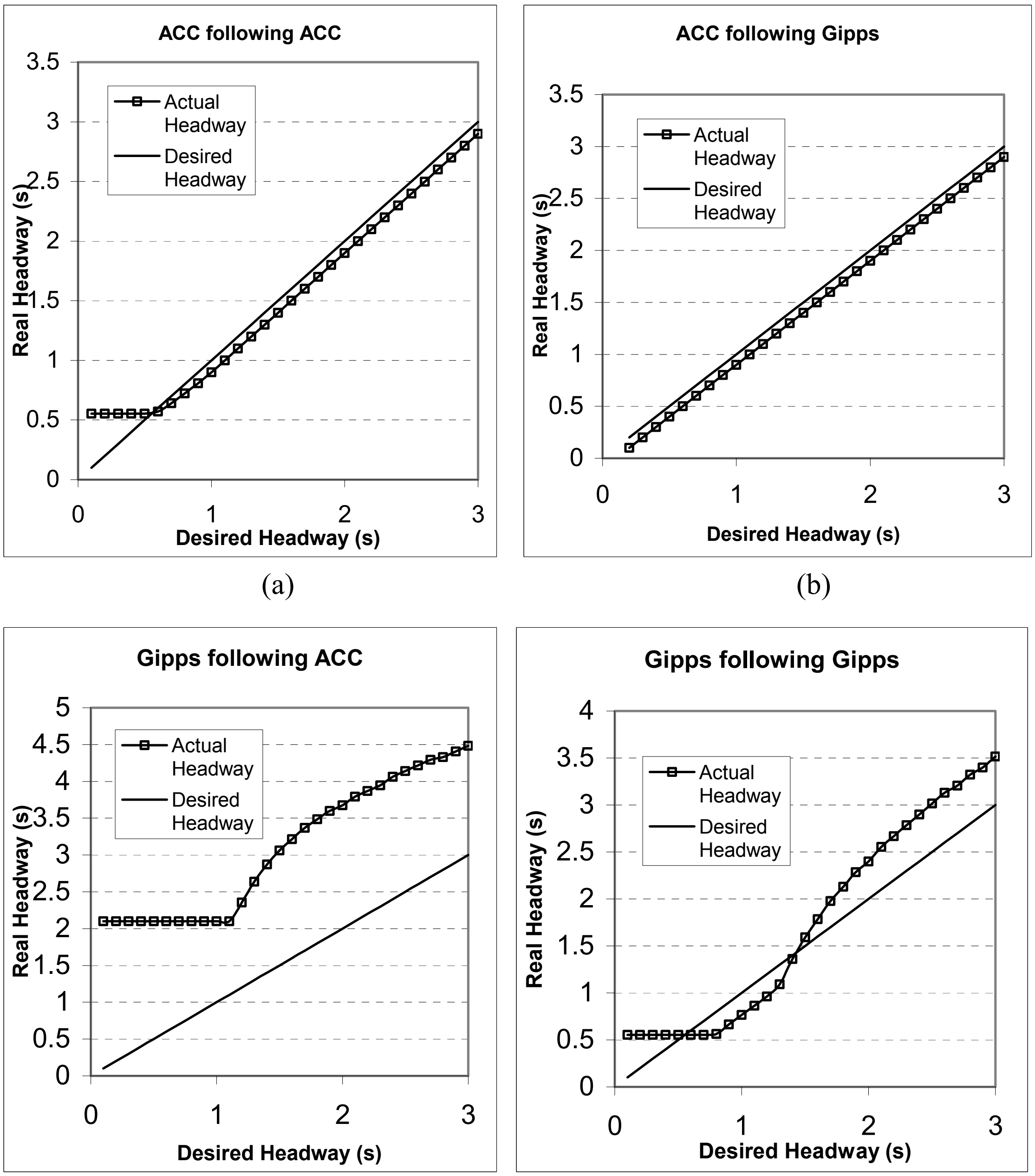
Figure 7. Single Vehicle's Following Behaviors

3.2 HEADWAY RESPONSE OF 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 certain time headway. In 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 8 shows the time headway response of ACC vehicle and Gipps' vehicle. The setting (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 emergency situations or in the case of congestion.

The real headway response is shown by the curve with marker in each graph. It is shown that ACC vehicles can always achieve the setting 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 can see, the Gipps' vehicle cannot catch the ACC vehicle. That is 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 the same amount of errors for human drivers.



(a) (b) (c) (d)

Figure 8. Headway Response Of Single Vehicle

By comparing these results, we conclude that the headway response of ACC vehicles can fulfill the requirement that will bring into potential of high capacity. Gipps' model can emulate the human drivers' behavior to some extent. The traffic flow comprised by these two kinds of vehicles is a mixed flow with heterogeneous headway behaviors.

3.3 SYSTEM RESPONSE TO INTERNAL PULSE

The system response to an internal disturbance is shown in Figure 9. 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 9, which is the case of 100% ACC penetration, the speeds of some vehicle are reduced to maintain safe distance. After the speed of the leading vehicle is restored, the affected vehicles can return to normal speeds.

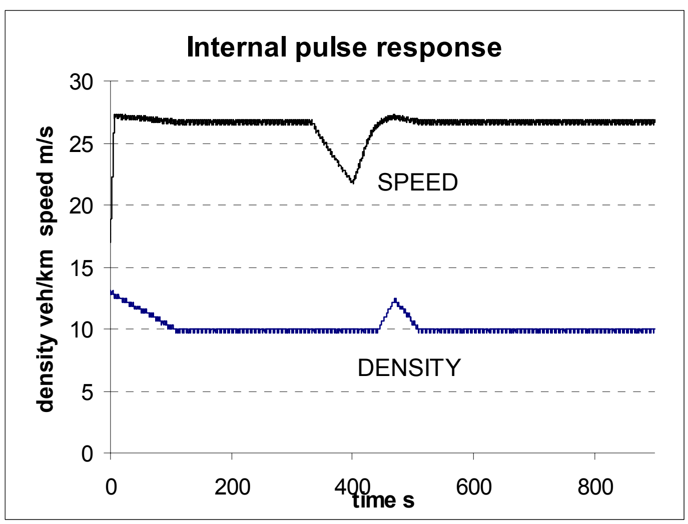


Figure 9. Density and Speed Profiles in an Internal Pulse

Furthermore, the restored platoon is running under a one-second time headway, 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 ACC has the potential to stabilize the traffic under small disturbances.

3.4 SYSTEM RESPONSE TO EXTERNAL PULSE

What we are most interested in is the response of the mixed traffic to the external disturbance that is generated by the pulse demand as shown in the Figure 5. 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 10 to Figure 13. 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 inverse proportional relation, while high penetration of ACC can increase the system speed in the pulse.

(c) The density-flow rate curves show a linear relationship in the un-congested 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 behaviors among ACC vehicles and manual vehicles.

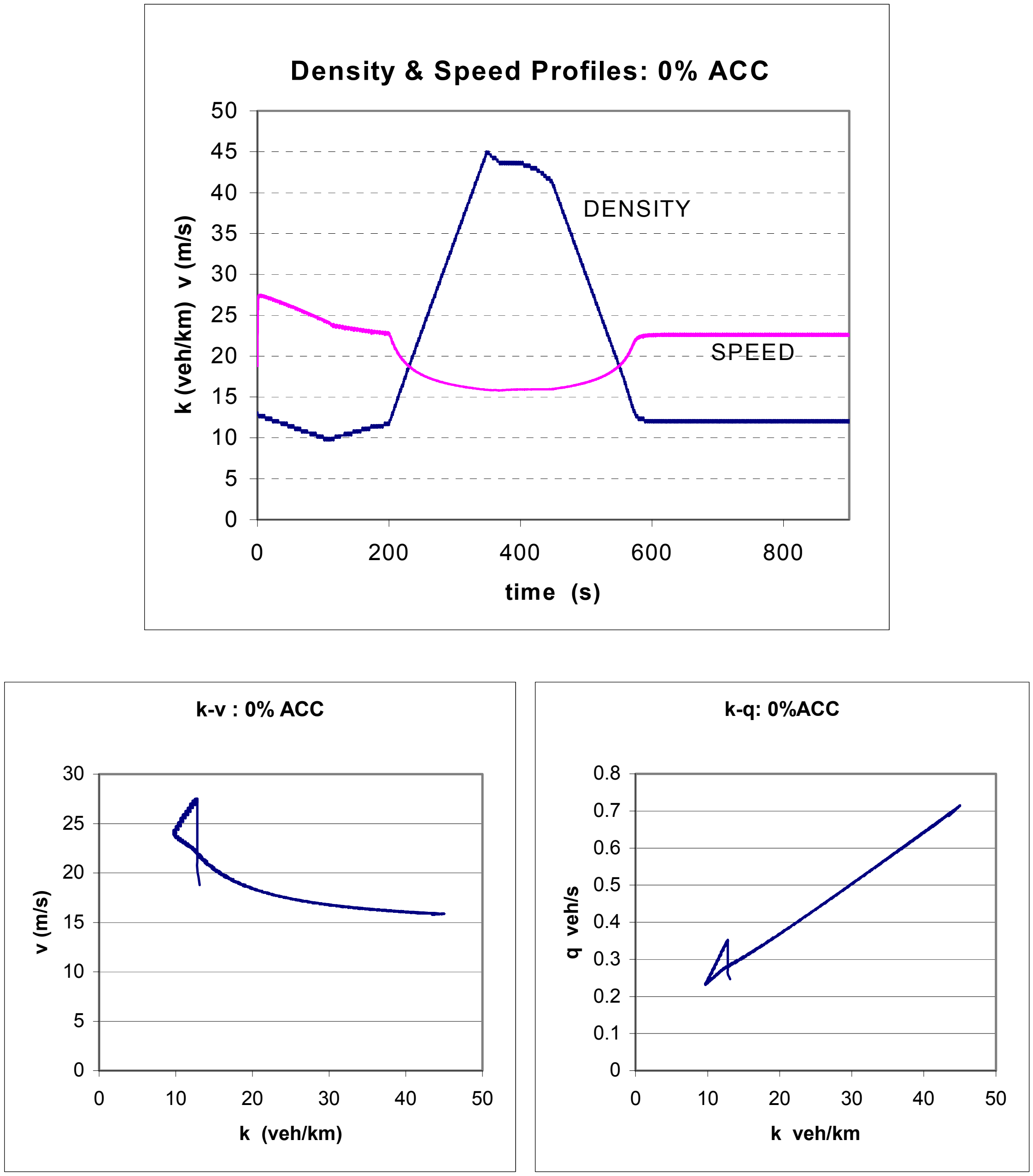


Figure 10. Response of 0%ACC system to External Impulse

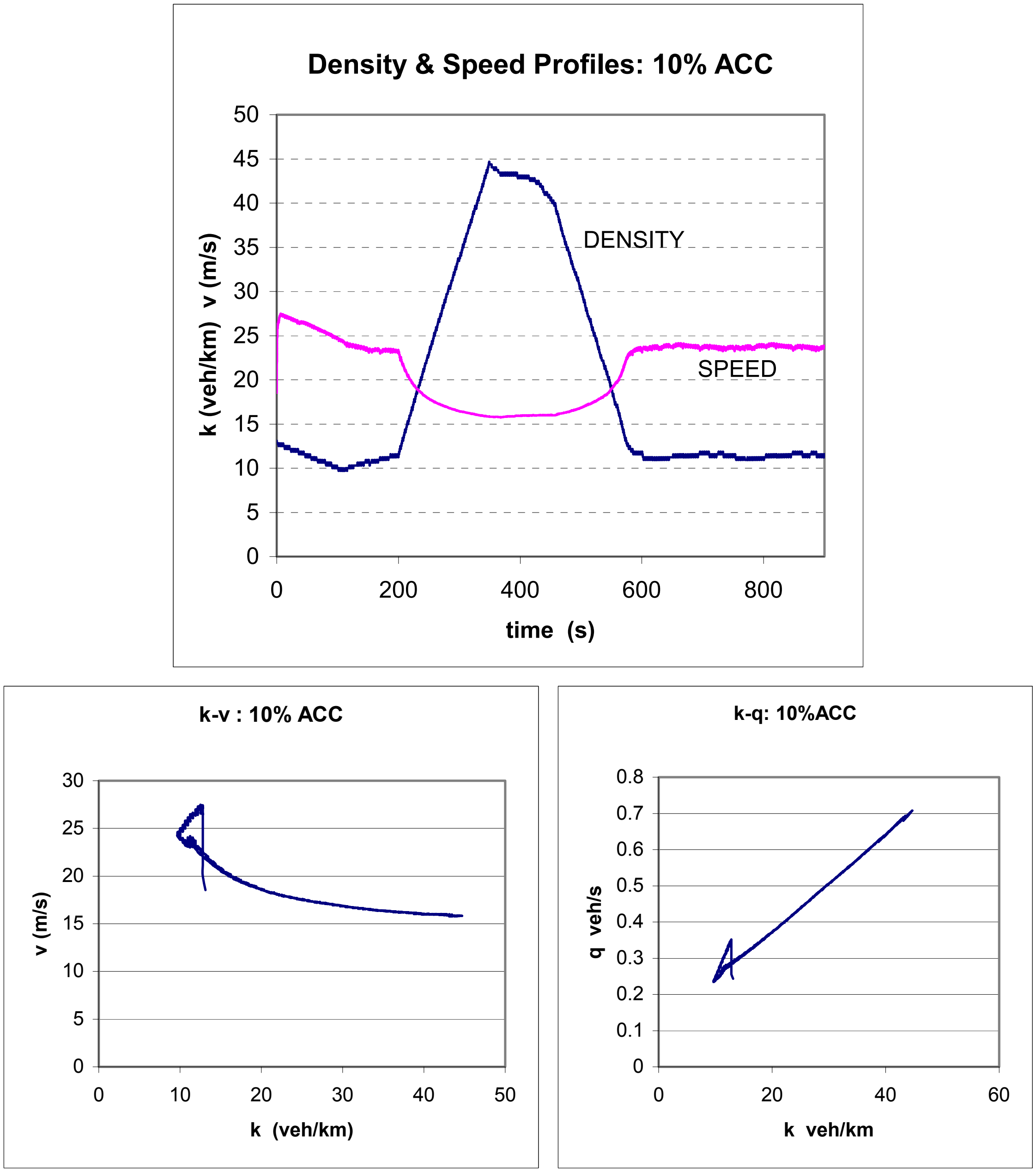
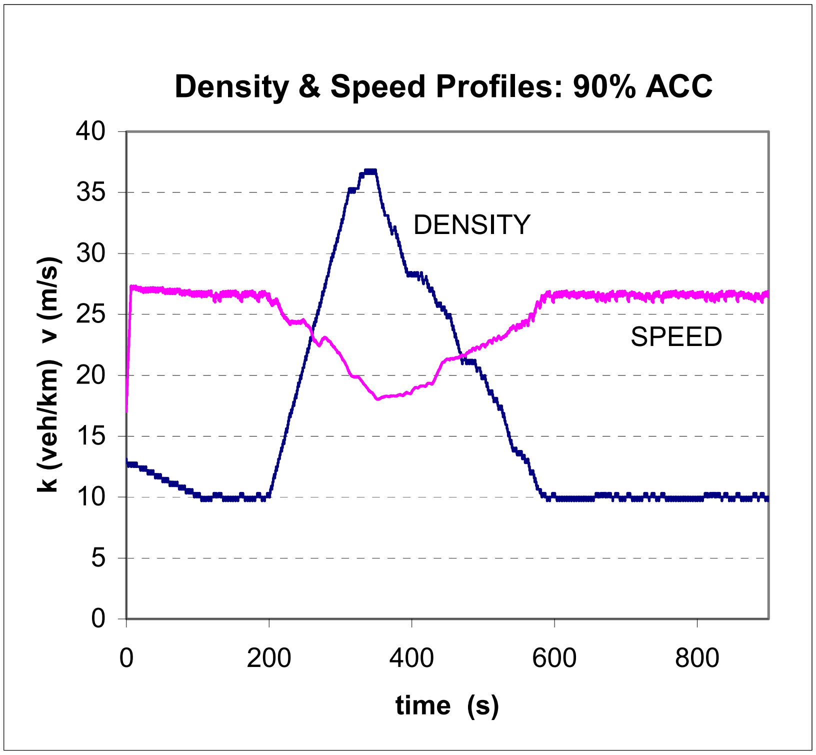
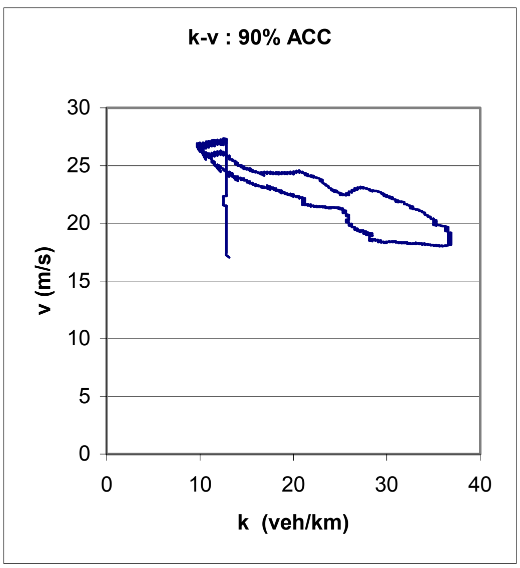


Figure 11. Response of 10%ACC system to External Impulse





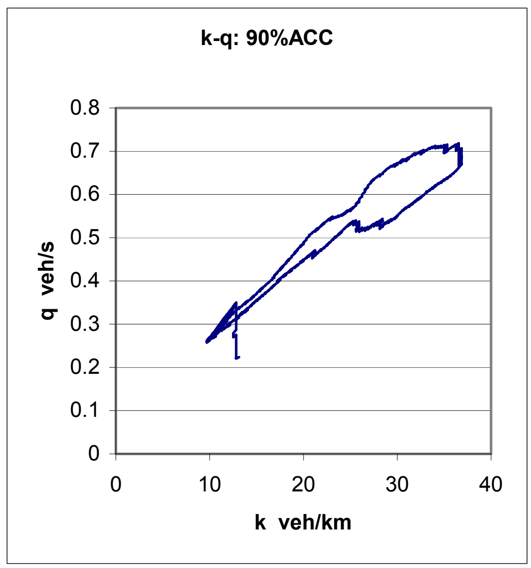


Figure 12. Response of 90%ACC system to External Impulse

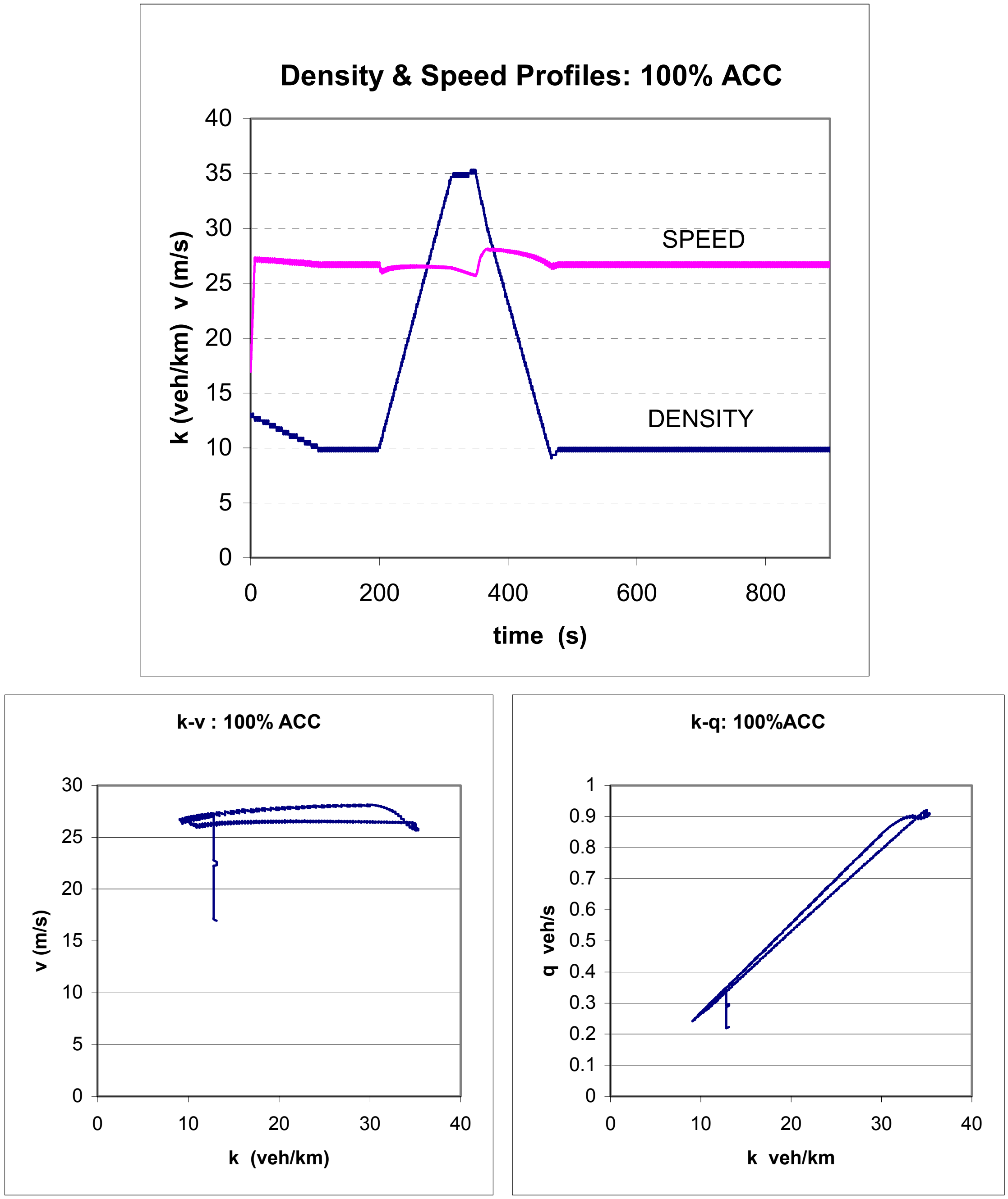


Figure 13. Response of 100%ACC system to External Impulse

3.5 SPEED PROFILES OF TRAFFIC FLOW WITH DIFFERENT ACC PENETRATION

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 14.

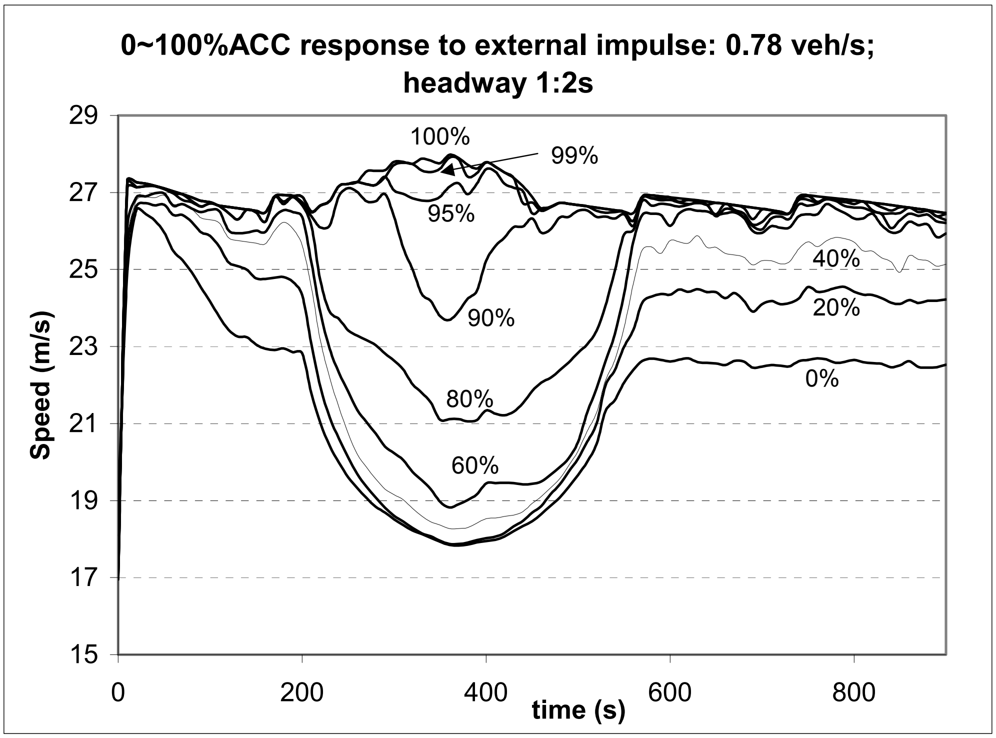


Figure 14. Speed Profiles under Different ACC Penetrations

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 restore to 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 is happened between 90% and 100% penetration. This means that high penetration of ACC 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. A tentative explanation of this phenomenon is that because of the high inflow rate of the demand, more vehicles on the road accelerate to the maximum speed than that under the normal case. In other words, a smaller portion of vehicles on the road are in the process of acceleration. As we can see in Figure 15, the proportion of low speed vehicle is zero in the peak of the speed profile. In the calculation, a vehicle with the speed lower than 20 m/s is called a low speed vehicle. 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.

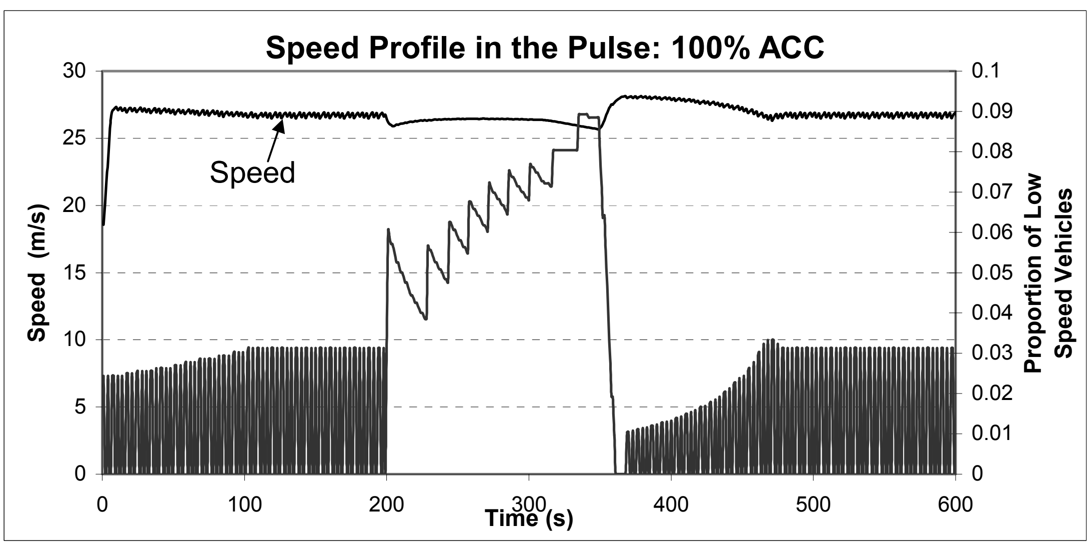


Figure 15. Speed Profile in Pulse

3.6 K-V AND K-Q 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 results 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 and is restored to normal state. Figure 16 shows the k-q and k-v curves for a 100% ACC system that encounters an over-capacity demand. It is shown that k-q curve is linear 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 17 compares the cases that 0% ACC system and 100% ACC system encounter at near-capacity saddle demand. It is obvious that 100% ACC system has a higher speed and lower density than a 0% ACC system.

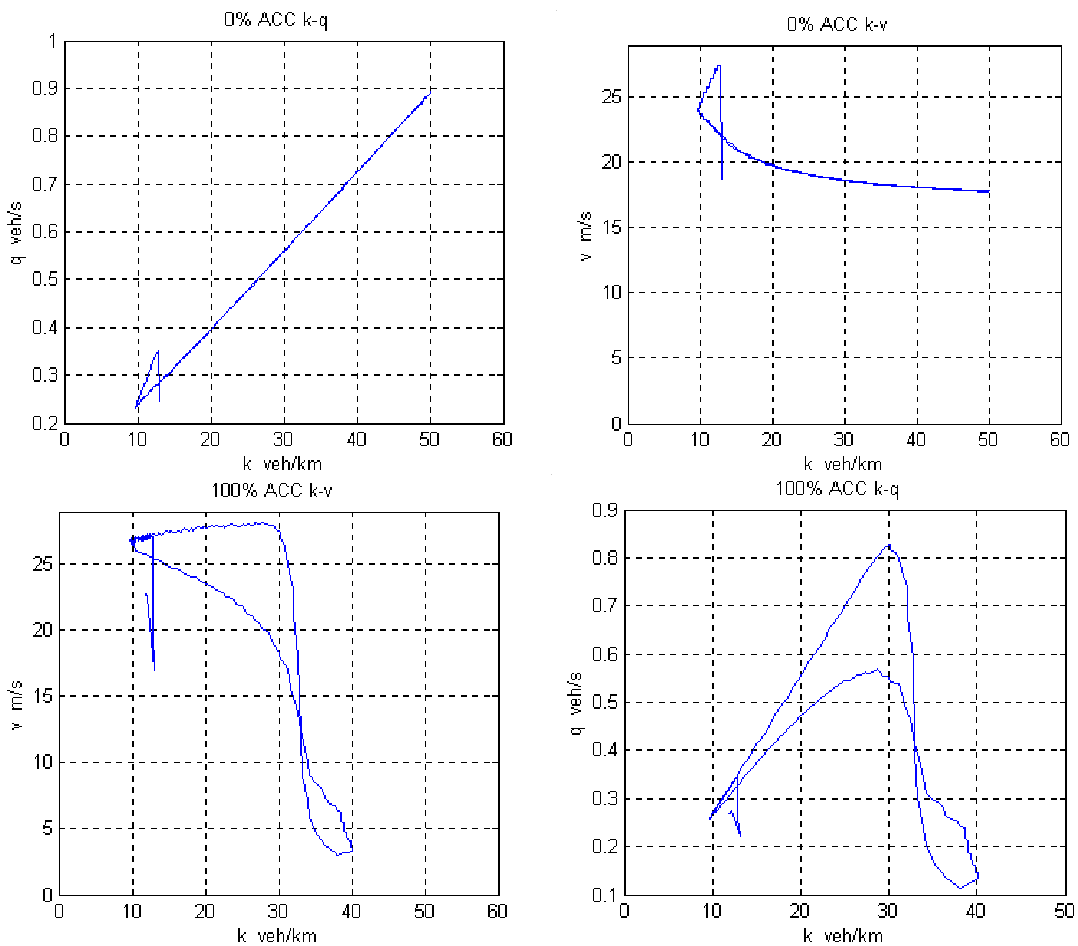


Figure 16. k-q & k-v Relation of Dynamic Process (Beyond Capacity)

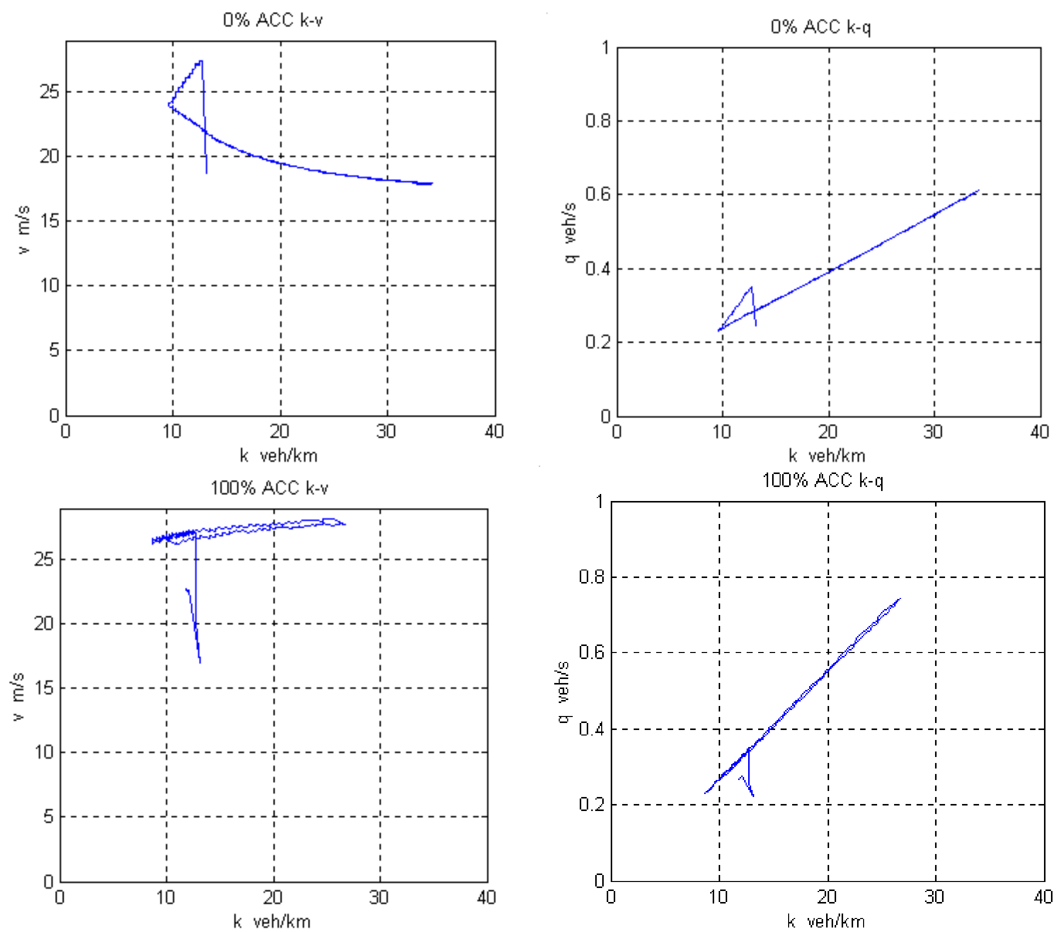


Figure 17. k-q & k-v Relation of Dynamic Process (Under Capacity)

3.7 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:

$$h_a = h_{acc} p + h_{man}(1 - p) \tag{18}$$

where: h_a: average headway

h_{acc}: headway of ACC vehicles

h_{man}: headway of manual vahicles

p: proportion of ACC vehicles

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

$$q = 3600 / h_a \tag{19}$$

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

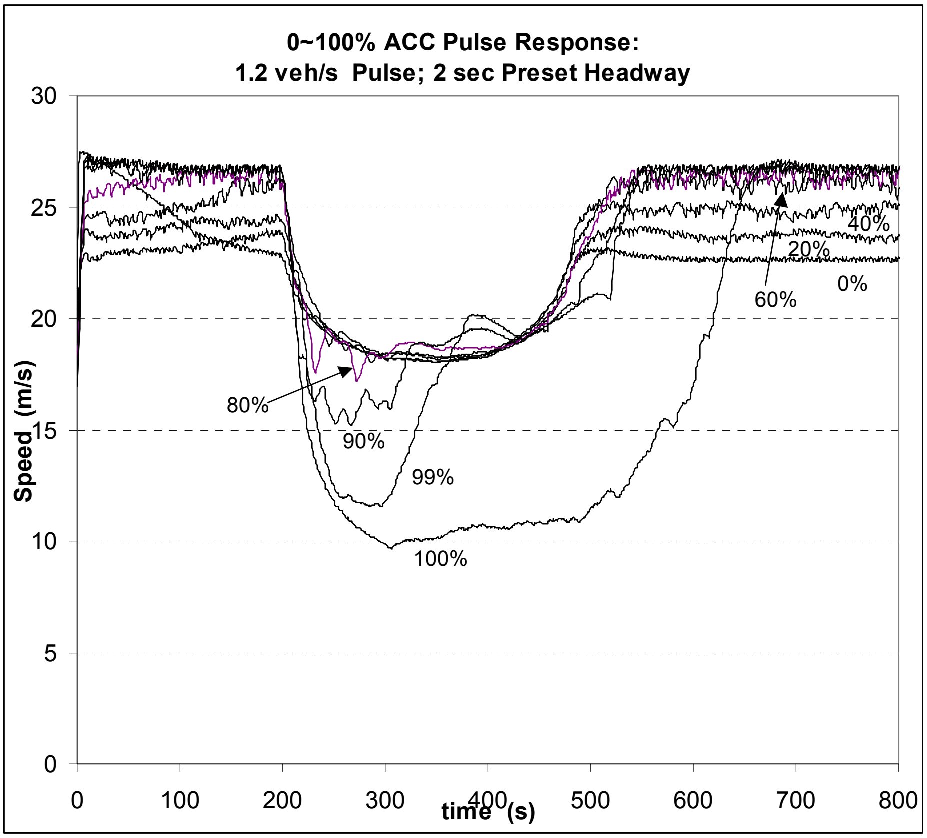


Figure 18. Speed Profiles under Different ACC Penetrations

On the other hand, there is a serious disadvantage of constant time headway 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 18. In this case, the differences of the system in pulse with various proportions of CTH vehicles are rather small and the benefits of high penetration of ACC are non-existent. There is an adverse effect if penetration of ACC is higher than a limit. This result shows CTH is not capable of reducing congestion in high demand condition.

3.8 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 CTH ACC vehicles will generate more oscillations in the patterns of the speed, as shown in Figure 19. This effect is more serious if the proportion is very high (greater than 95%). In the stable range with low proportion of CTH vehicles, the variance is always small.

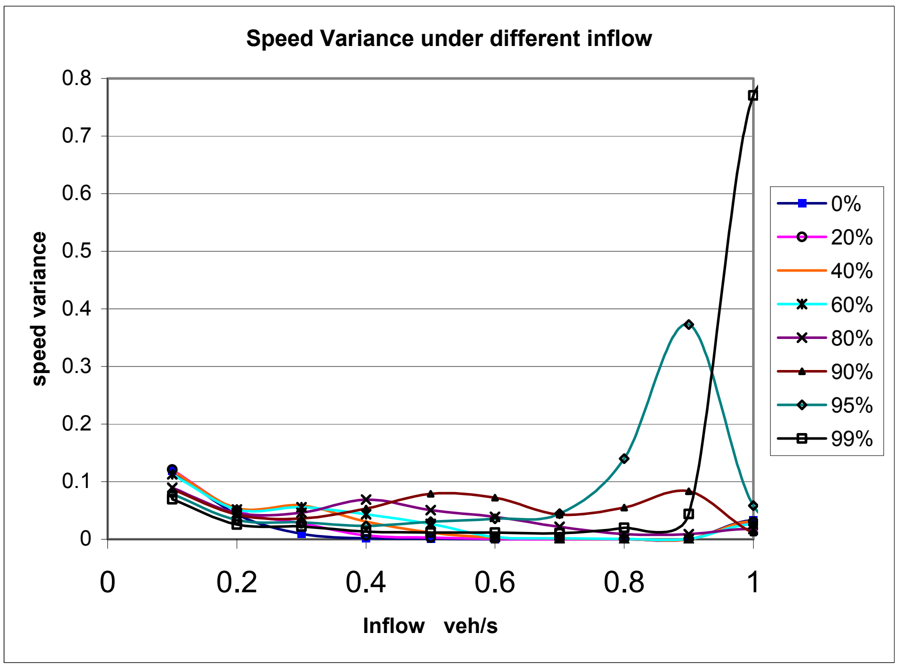


Figure 19. Speed Variance under Different Inflow and Different ACC Penetration

On the other hand, the speed variances discussed here may not accurately represent the real value, because the road is rather short (3.2 km) and the number of vehicles is small. We can expect smaller variance in a larger system.

3.9 QUEUE ON THE ROAD AND TRAVEL TIME

Another method to evaluate mixed traffic is to measure the length of queue and the travel time of vehicles. Figure 20 compares the number of vehicles on the road under different ACC penetrations. In this case, the pulse of the inflow rate, as shown in Figure 5, is just the upper limit of ACC capacity. As we can see, the numbers of vehicles on the road during high ACC penetration scenarios are smaller than that of pure manual traffic in the pulse. It means less congestion in this section of the road. On the other hand, the duration of congestion is shorter with high ACC penetrations than with pure manual traffic.

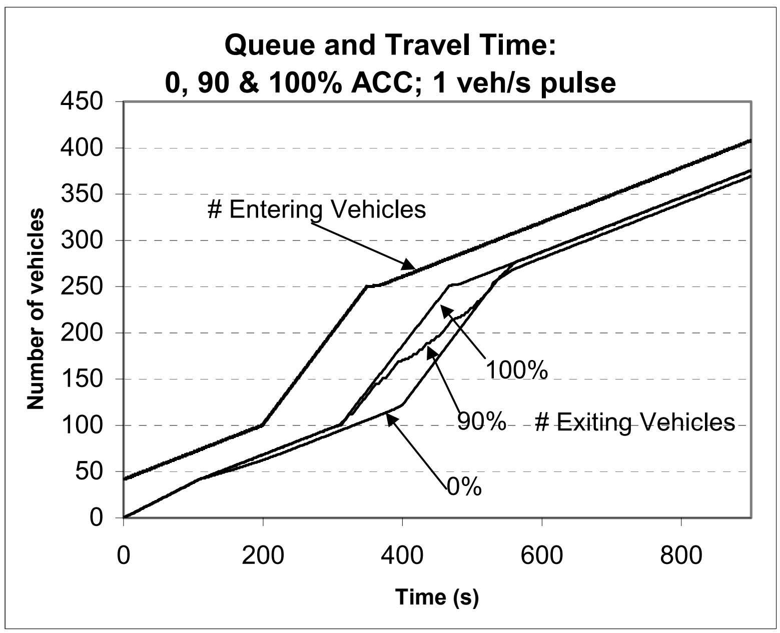


Figure 20.

As we discussed before, it is a property of CTH ACC system that it cannot cope with high demand flow rate beyond its capacity, which is determined by its preset headway. In the case that the inflow rate is higher than the capacity of ACC, we see a decrease of capacity. As shown in Figure 21, the numbers of vehicles under high ACC penetrations are larger than the former cases.

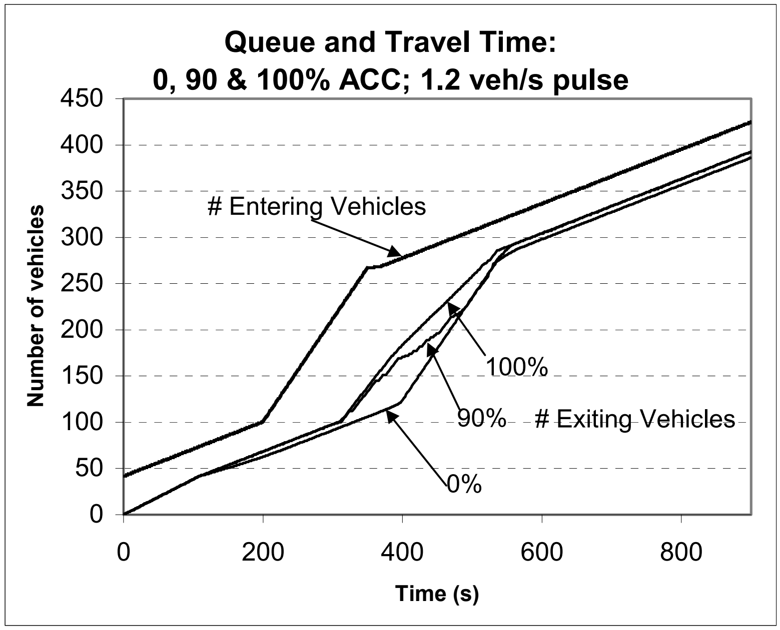

Queue and Travel Time:
0, 90 & 100% ACC; 1.2 veh/s pulse
450
400
350
300
250
200
150
100
50
0
Number of vehicles
Entering Vehicles
100%
90%
Exiting Vehicles
0%
0
200
400
600
800
Time (s)

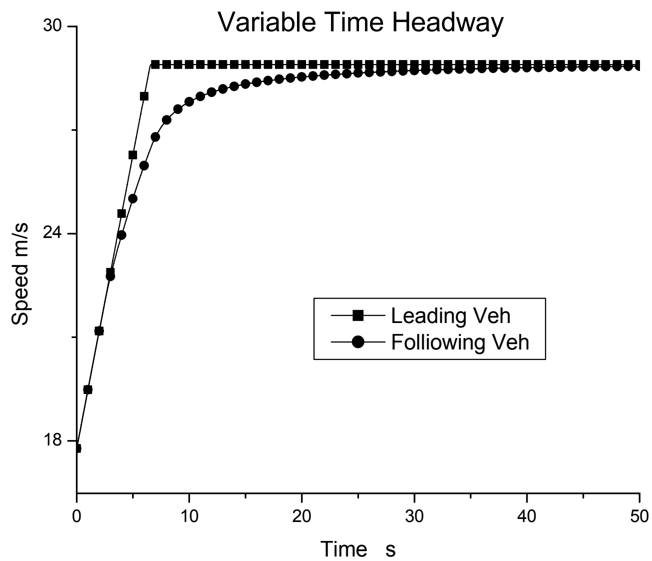
Figure 21.

4

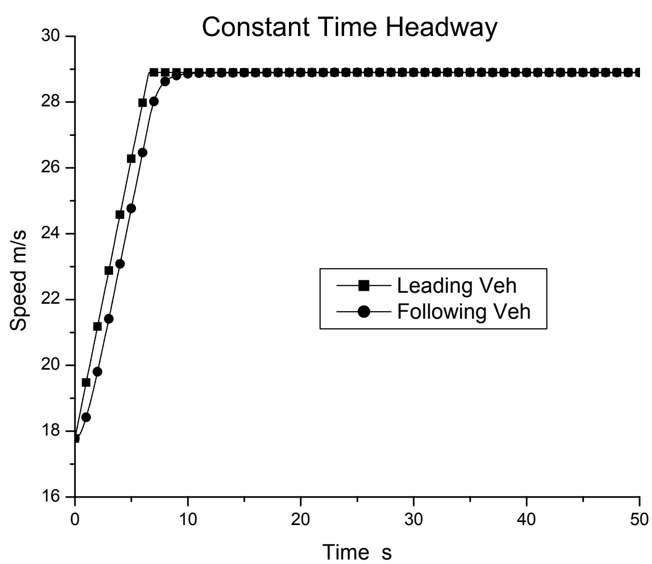
Comparison Of Variable Time Headway And Constant Time Headway

4.1 SINGLE VEHICLE FOLLOWING BEHAVIOR

The typical single car following behaviors is shown in Figure 22. 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 takes 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-gap. 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.



(a)



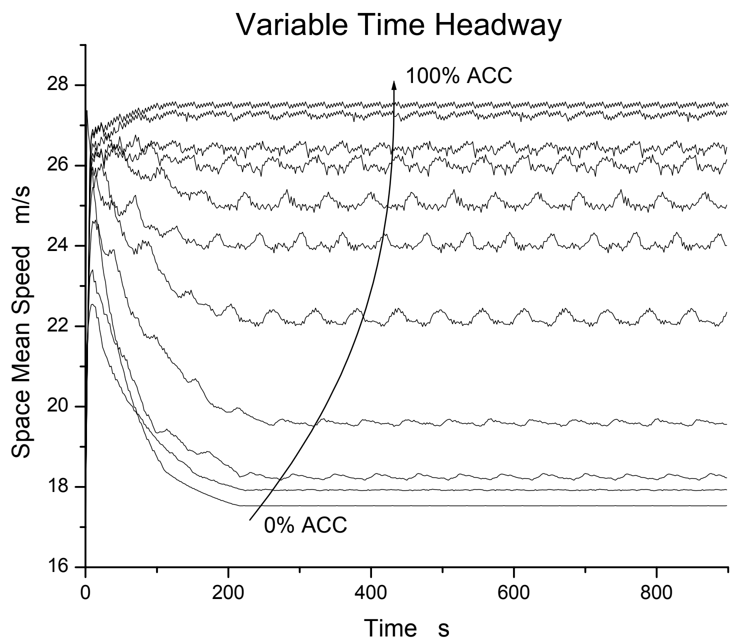
(b)

Figure 22. Single Vehicle's Following Behavior

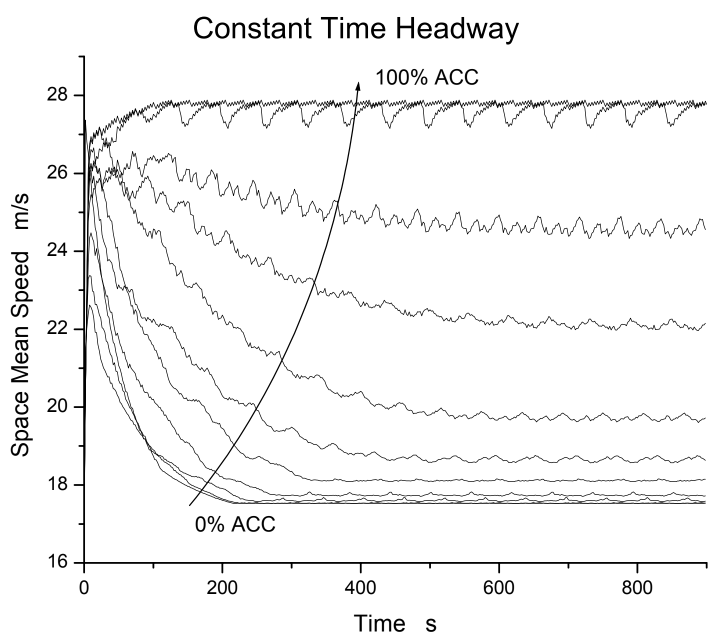
4.2 SPEED PROFILES OF TRAFFIC FLOW WITH DIFFERENT ACC PENETRATION

Under different constant demands, the mixed traffic of VTH cars performs better than those of CTH cars. As shown in Figure 23, under the same demand, the speed of VTH traffic is always higher than CTH traffic except the 100% case, and they always have shorter response time to reach the steady state.

The mixed traffic has larger speed oscillations than the cases of pure ACC traffic or pure manual traffic. 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 CTH control ACC vehicles will generate more oscillations in speed, as shown in Figure 24. This effect is more serious if the proportion is very high (greater than 95%). In the stable range with low proportion of CTH vehicles, the variance is always small. On the other hand, a little higher speed variance is found with VTH vehicles, as shown in Fig. 26. But this phenomenon is reversed in the cases of very high ACC penetration, such as 99% and 100%.


Variable Time Headway
100% ACC
0% ACC
Space Mean Speed m/s
Time s
16
18
20
22
24
26
28
0
200
400
600
800

(a)


Constant Time Headway
100% ACC
0% ACC
Space Mean Speed m/s
Time s
16
18
20
22
24
26
28
0
200
400
600
800

(b)

Figure 23.

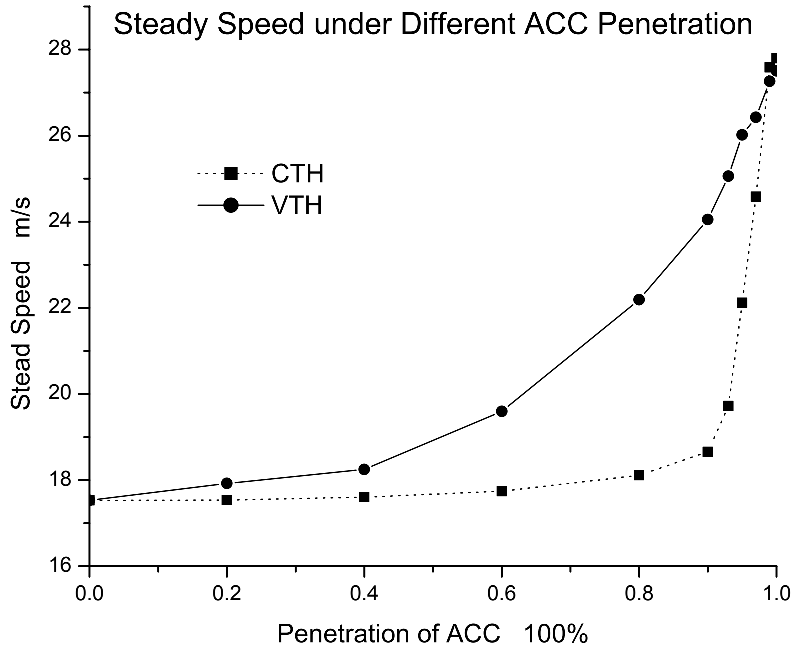


Figure 24.

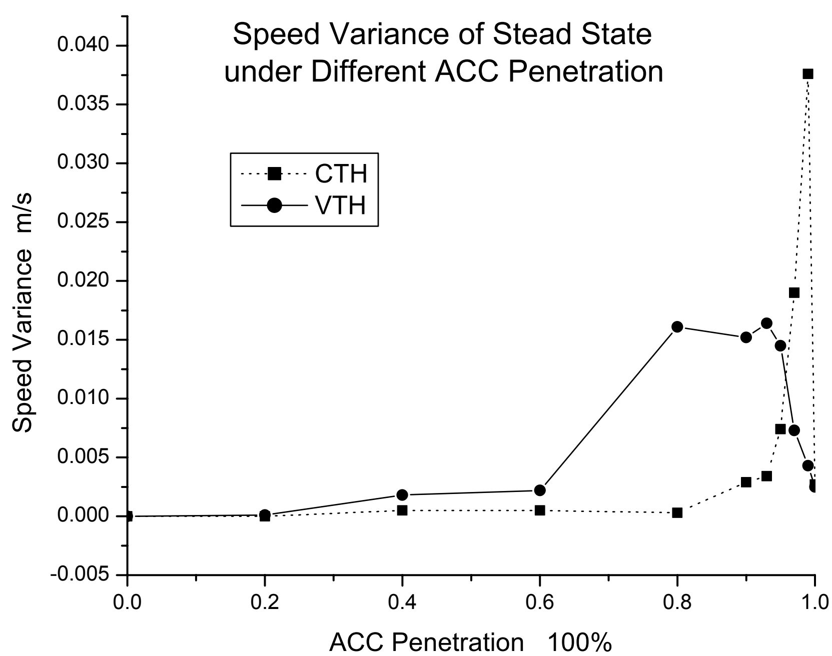


Figure 25.

4.3 SYSTEM RESPONSE TO EXTERNAL PULSE

After exerting the same disturbances in the system with different ACC vehicle penetrations we can compare the speed profiles and get the impacts of ACC on the mixed traffic, as shown in Figure 26. As we can see, the penetration of ACC will significantly affect the speed profiles:

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

(b) High penetration of VTH 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.

4.4 K-V AND K-Q RELATION IN MIXED TRAFFIC

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). Figures 27 and 28 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 28 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.

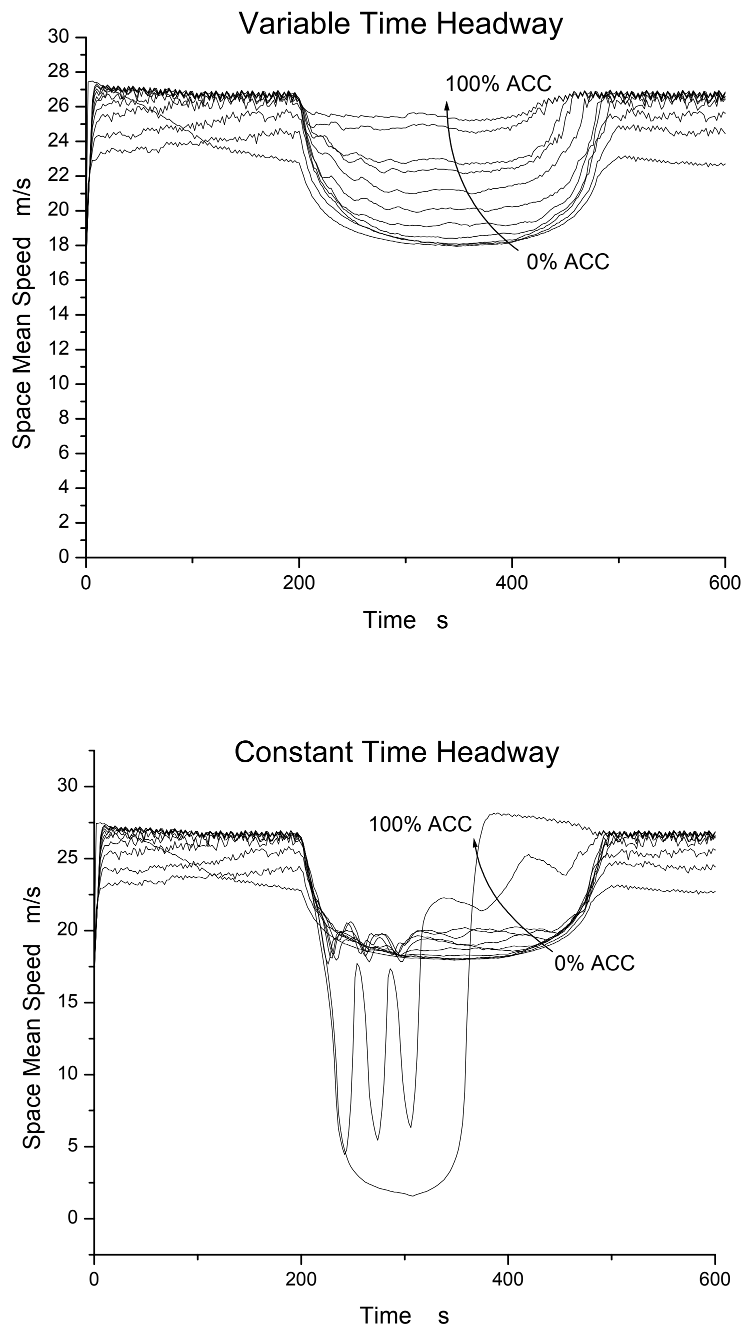


Figure 26. Speed Profiles of Traffic Flow with Different ACC Penetration

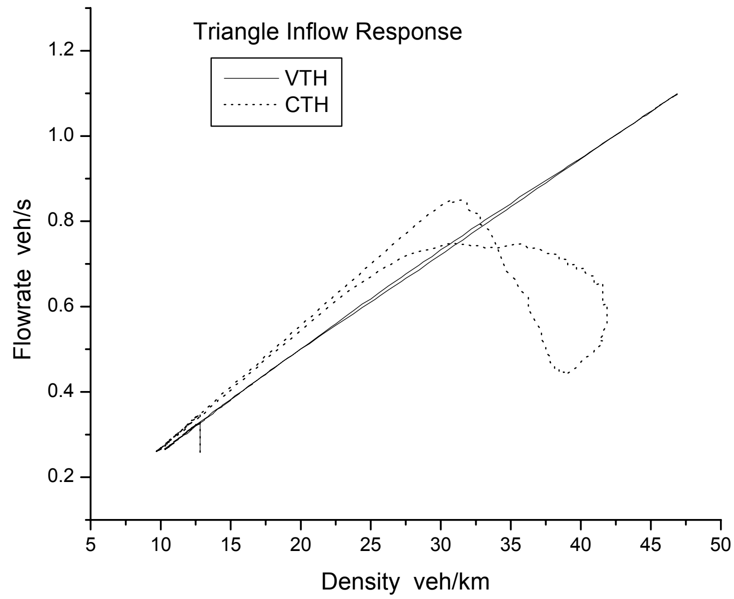


Figure 27.

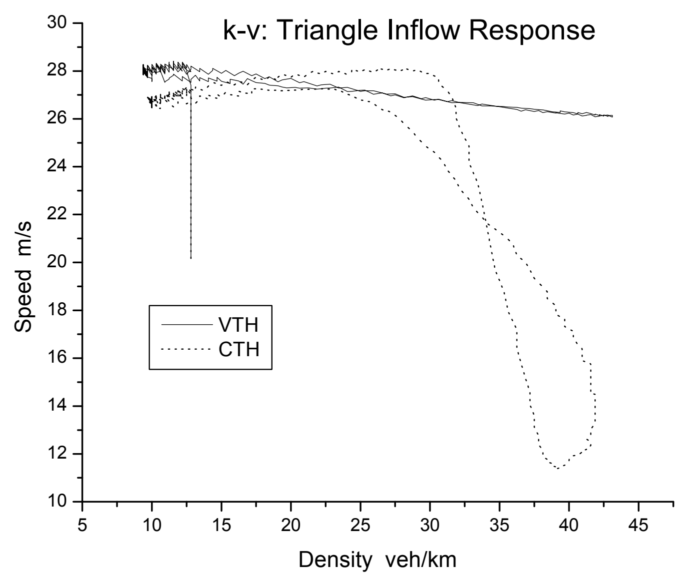


Figure 28.

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. 30. The response process is shown in Fig. 31. 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.

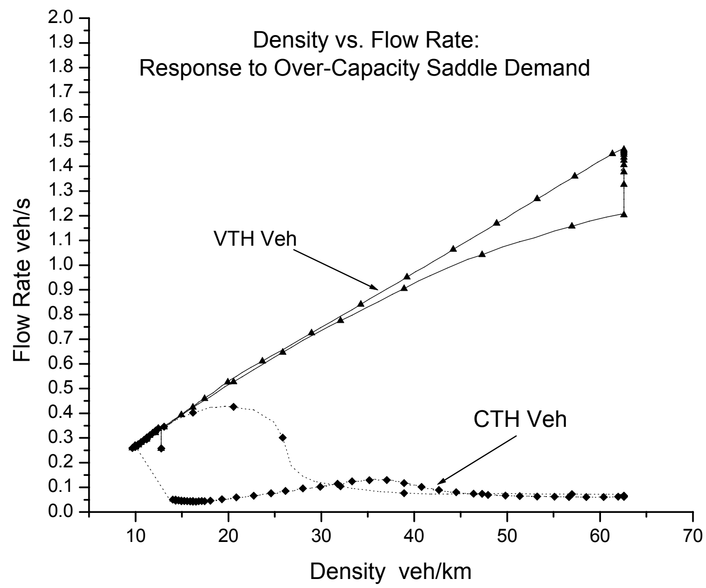


Figure 29.

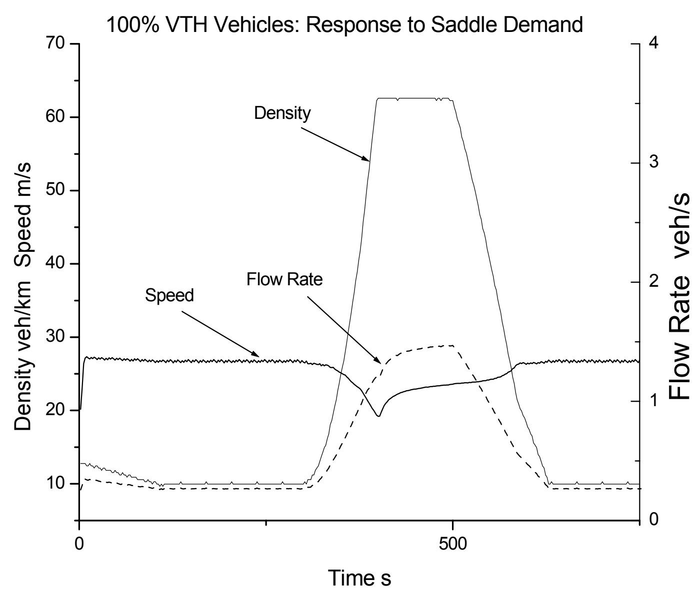


Figure 30.

5

SIMULATION WITH SOME RANDOM EFFECTS

5.1 INTRODUCTION

As a simplified analysis, the simulations in Chapter 3 do not include the variation of headways among ACC and manual driven vehicles. To make the simulation more realistic, a randomly chosen headway is implemented in simulation. It is assumed that each driver keeps his/her favorite headway all the time. A new attribute of vehicle class: vehicle.headway is preset in the vehicle generation procedure, which determines the headway choice of each vehicle and cannot be changed during simulation. 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 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. A normally distributed random number is generated in function: float gasdev(long *idum). Experimental results are summarized below:

5.2 MIXED TRAFFIC OF CTH AND MANUAL DRIVEN VEHICLES

Five combinations of CTH and manual driven vehicles with different headway distributions are simulated, which include:

(1) CTH=1 sec; Gipps= 2 sec, as shown in Figure 31;

(2) CTH=1 sec; Gipps= max(2+ N(0,1), 1) sec, as shown in Figure 32;

(3) CTH=1 sec; Gipps= max(2+ N(0,1)*2, 1) sec, as shown in Figure 33;

(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 34;

(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 35.

As one can see, the random headways of manual driven vehicles do not have much influence on the performance of traffic. In contrast, the random headways of CTH ACC vehicles greatly affect the traffic. Higher headway deviation of CTH vehicles will lead to higher speed drop and oscillations, especially when the ACC penetration is very high. In the case of 100% CTH ACC penetration, higher headway deviation results in serious speed drop and longer time to recover.

Figure 36 presents the comparison of the average speed in the five CTH experiments; Figure 37 presents the comparison of the speed variance. As one can see, high penetration of CTH ACC increases the average speed in most of cases. But high headway deviation deteriorates this effect. On the other hand, the speed variance is not significant in most of case, except the case of 100% ACC penetration under high headway deviation. It can be concluded that these results can not provide support of the claim that CTH ACC will add traffic capacity.

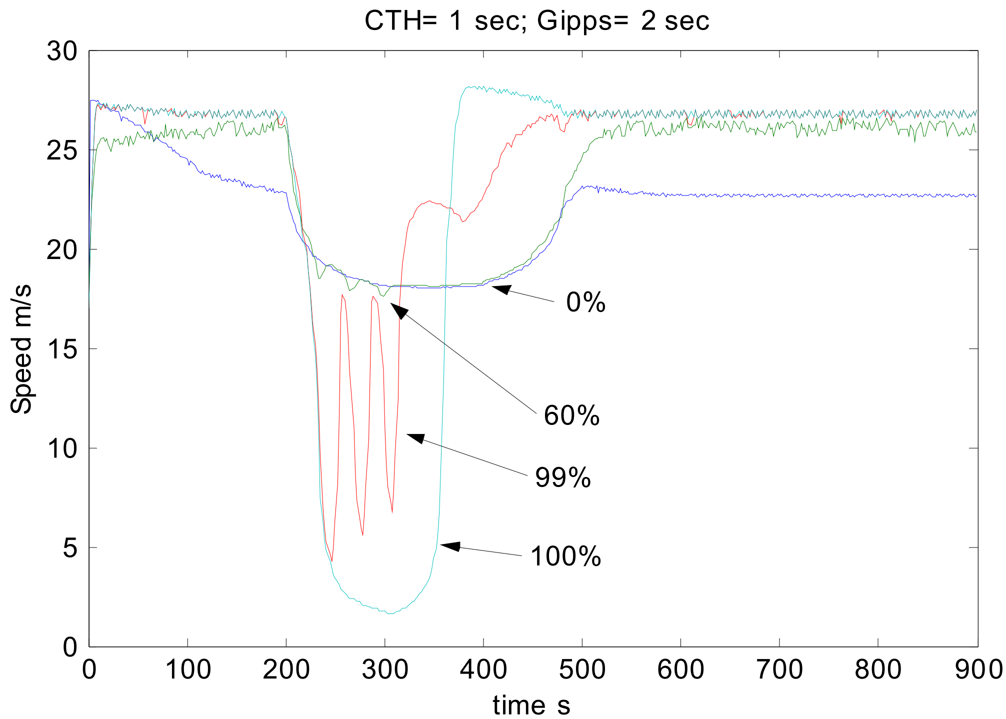


Figure 31.

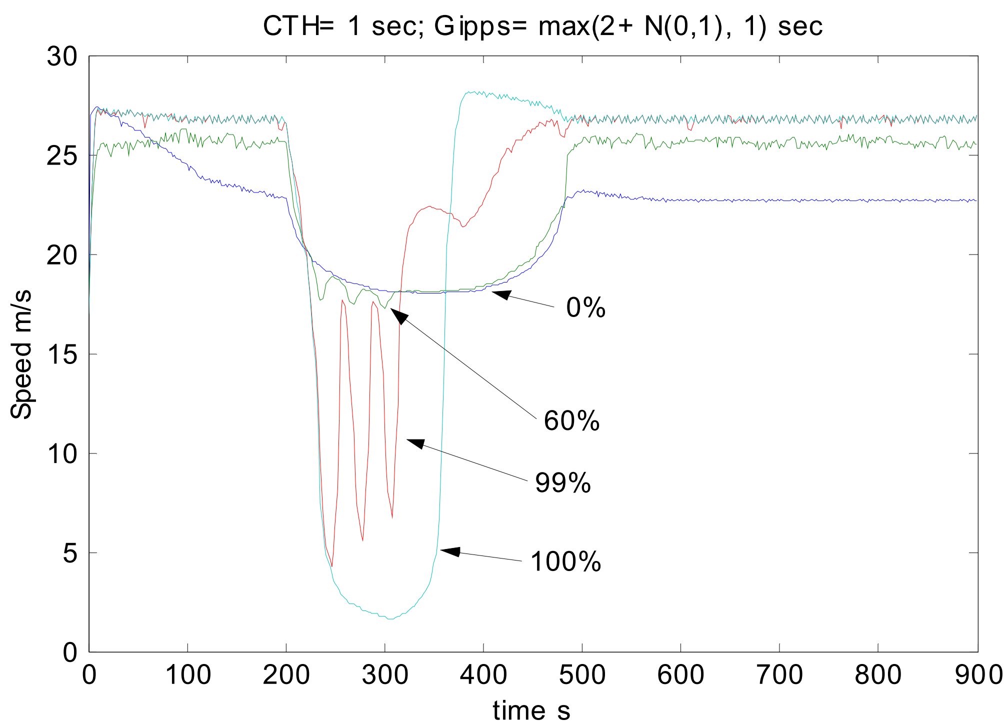


Figure 32.

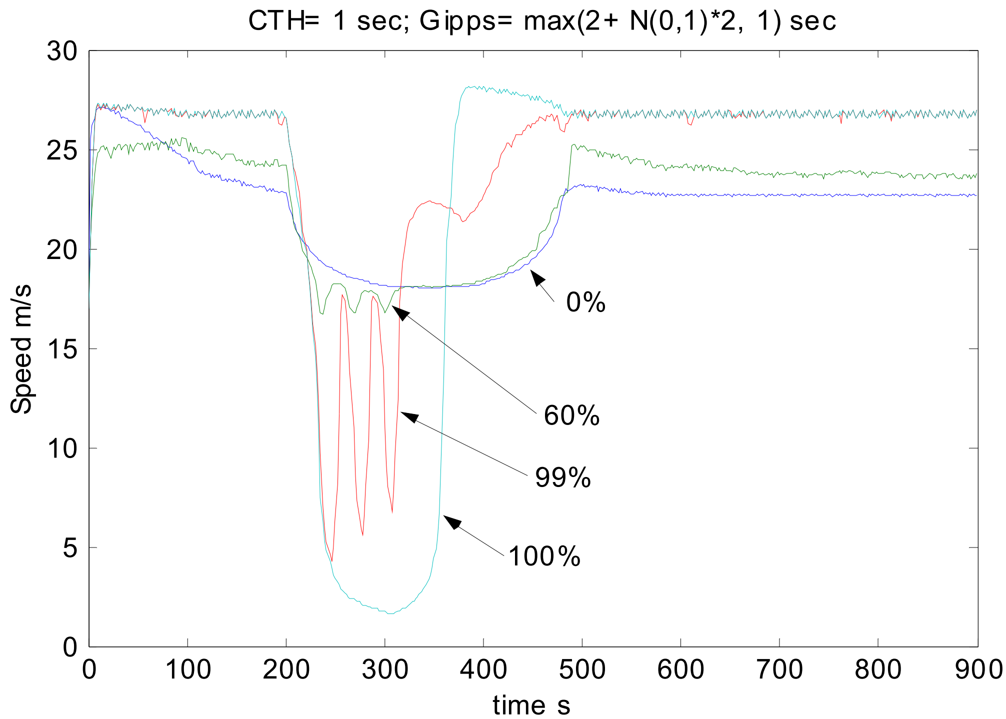


Figure 33.

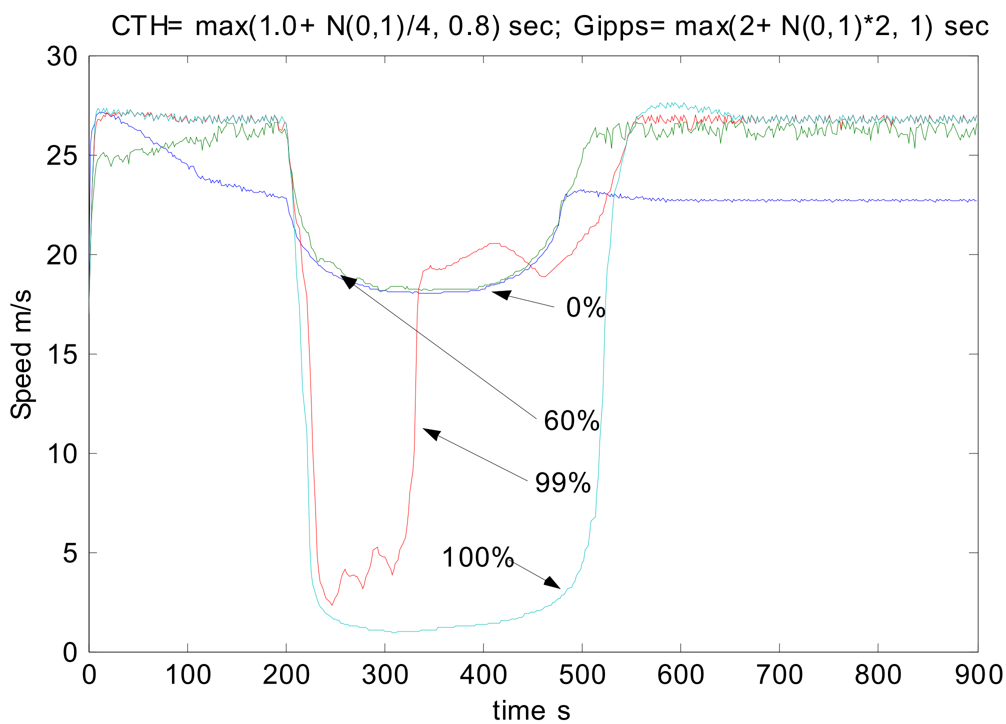


Figure 34.

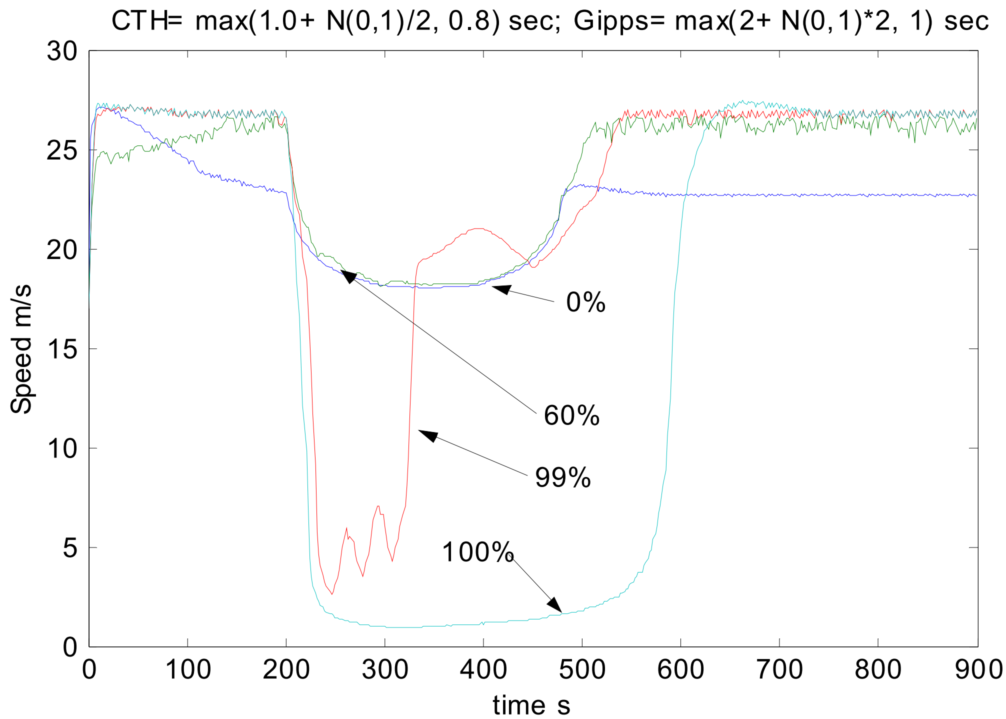


Figure 35.

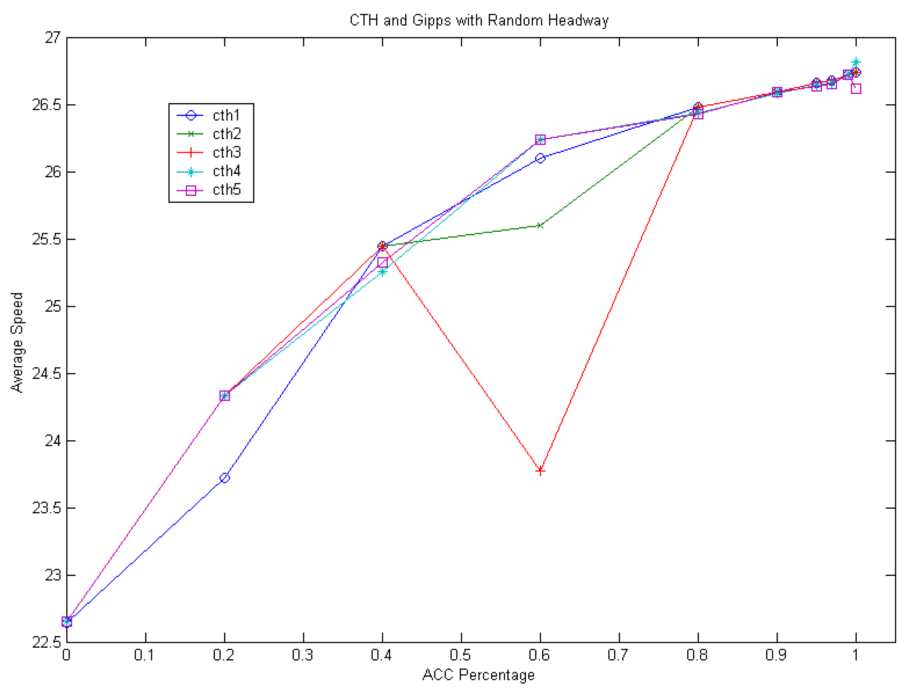


Figure 36.

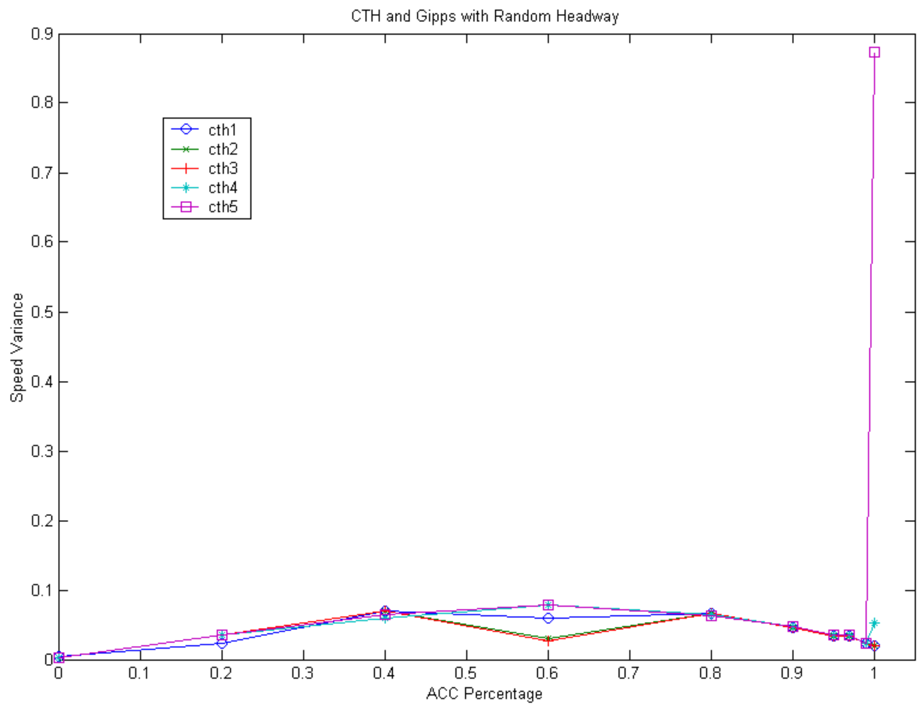


Figure 37.

5.3 MIXED TRAFFIC OF VTH AND MANUAL DRIVEN VEHICLES

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

(1) VTH and Gipps =2 sec, as shown in Figure 38;

(2) VTH and Gipps = max(2+ N(0,1), 1) sec, as shown in Figure 39;

(3) VTH and Gipps = max(2+ N(0,1)*2, 1) sec, as shown in Figure 40.

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 driven vehicles. It is shown that VTH ACC always performs well facing different headway deviation of human driver.

Figure 41 presents the comparison of the average speed in the three VTH experiments; Figure 42 presents the comparison of the speed variance. There is no significant difference in terms of speed and speed variance. These results further justify the advantage of VTH ACC compared with CTH ACC.

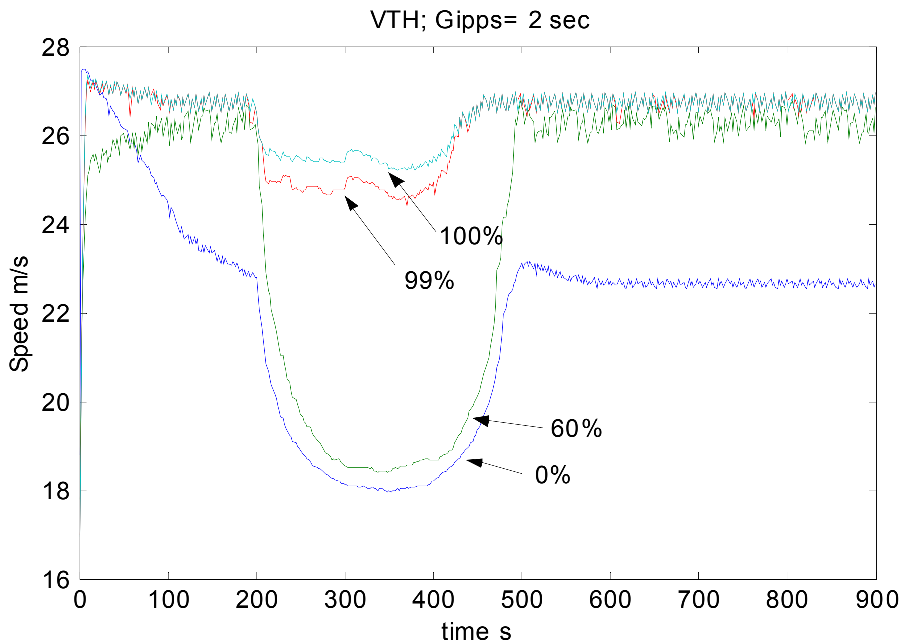


Figure 38.

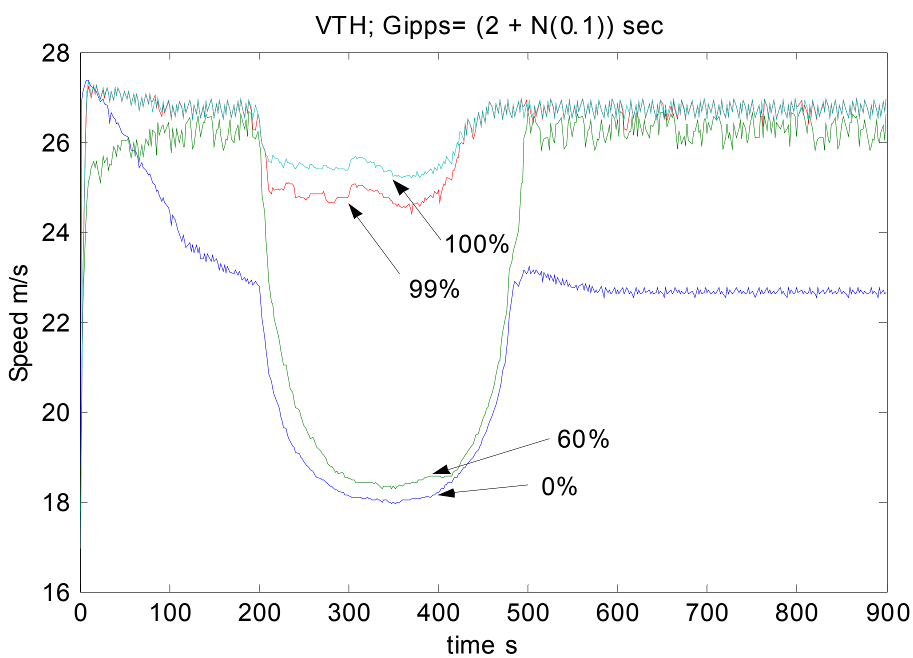


Figure 39.

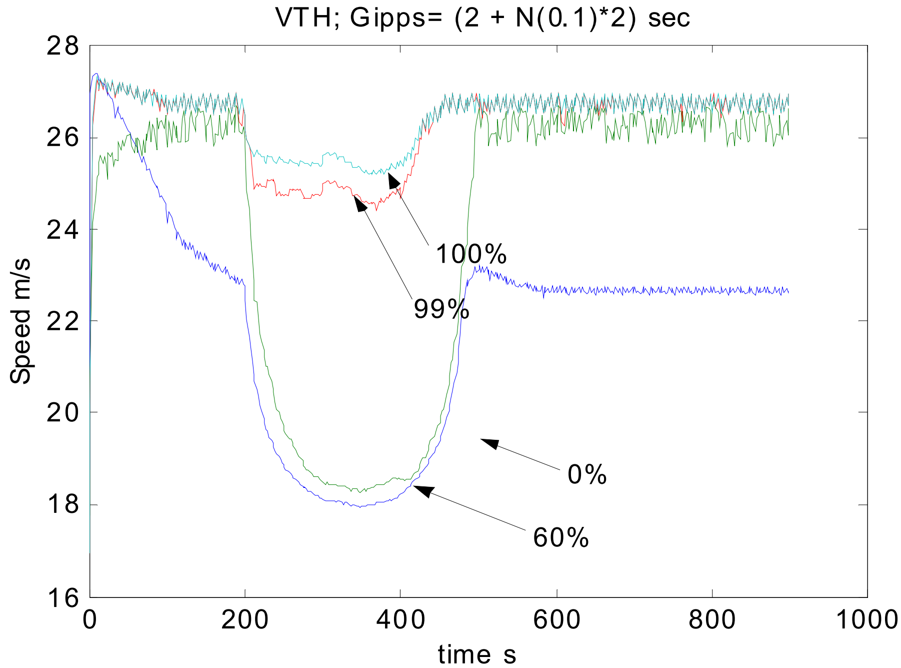


Figure 40.

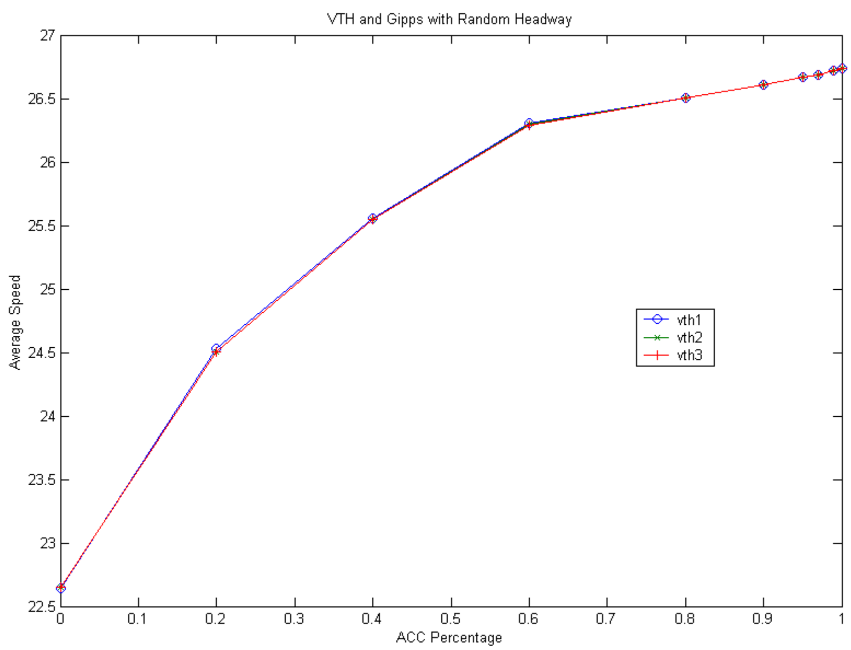


Figure 41.

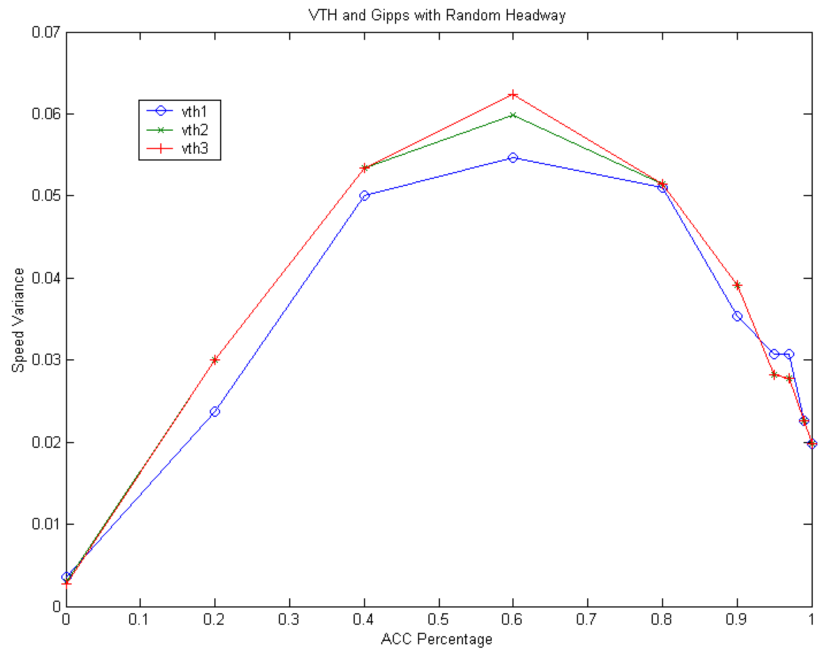

VTH and Gipps with Random Headway
vth1
vth2
vth3
Speed Variance
ACC Percentage
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Figure 42.

6

CONCLUSIONS

(1) To evaluate the impacts of ACC on the traffic flow and to find a better ACC algorithm, we designed a simulation 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. 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.

(2) 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 to oscillations that have negative fuel and environmental implications. For instance, if we use a constant time headway algorithm to achieve high speed, we find that a high (95 ~ 99%) penetration of CTH vehicles increase throughput. But it is at the expense of high speed oscillation at above capacity inflow rates. From a traffic flow perspective, constant time headway 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.

(3) 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.

(4) 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 the situations in which ACC and manual driven vehicles have different distributions of preset headway, it is concluded that the headway deviation doesn't have much impacts on the traffic performance in most of situations.

(5) Another direction of the work is to find the theoretical tools that can be used to analyze mixed traffic and quantitatively define traffic flow stability. This thesis presents a study based on the density-flow rate relation of real world traffic. The criterion function is effective in forecasting potential congestions. A definition of traffic flow stability is provided based on this criterion function. Further study in this direction is worthwhile.

REFERENCES

Ayres, T., L. Li, D. Schleuning, and D. Young (2001). Preferred Time-Headway of Highway Drivers," Proceedings of the 4th International IEEE Conference on Intelligent Transportation Systems.

Becker, S., Bork, M., Diriben, H.T., Geduld, G., et al., 1994. Summary of experience with AICC. Proceedings of the First World Congress on ATT and IVHS ERTICO. Brussels, Belgium.

Bickers, Charles (2000), Just Cruisin', Far Eastern Economic Review, July 13.

Bose, Arnab and Ioannou, Petros, (2001). Analysis of Traffic Flow With Mixed Manual and Intelligent Cruise Control Vehicles: Theory and Experiments, UCB-ITS-PRR-2001-13, California PATH Research Report, April.

Broqua, F., Lerner, G., Mauro, V., Morello, S., 1991. Cooperative driving: basic concepts and first assessment of intelligent cruise control strategies. Proceedings of the DRIVE Conference, ERTICO. Brussels, Belgium.

California Driving Manual (2001).

Chakroborty, Partha, Kikuchi, Shinya, 1999. Evaluation of the General Motors based car-following models and a fuzzy inference model, Transportation Research Part C 7 (1999) 209-235.

Daimler-Chrysler, (1998). Innovation Award 1998 The winning theme: Distronic, http://www.daimlerchrysler.com/index_e.htm?/news/top/1998/t81203a_e.htm, accessed by Xi Zou, Feb 24, 2002.

Darbha, Swaroop and Rajagopal, K. R., 1999. Intelligent cruise control systems and traffic flow stability, Transportation Research Part C: Emerging Technologies, Volume 7, Issue 6, December 1999, Pages 329-352.

Delphi Delco Electronics Systems(2001), Forewarn Adaptive Cruise Control (Radar), http://www.delphiauto.com/pdf/delcopdfs/ACCRadar.pdf, accessed by Xi Zou, Feb 24, 2002.

Eaton Vorad (2001), Eaton Vorad website:http://truck.eaton.com/vorad, accessed by Xi Zou, Feb 24, 2002.

EASi GmbH (2002) EASi Europe, ST_ORM Faq, webpage: http://www.easi.de/storm/faq.php3?css_ok=0, accessed by Xi Zou, Feb 24, 2002.

Fancher, Paul and Bareket, Zevi, 1995. The Influence of Intelligent Cruise Control Systems on Traffic Flow, JSAE Review, Volume 16, Issue 2, April 1995, Page 219.

FHWA(1999), U.S. Transportation Secretary Slater Announces $35 Million Joint Research With GM On Vehicle Crash Warning Systems, FHWA 40-99, June 24.

FORD (2001), FORD - FUTURE TECHNOLOGY WATCH, website: http://www.bonforums.com/tech/adaptivecruisecontrol.htm, copyright WWW.BlueOvalNews.Com, accessed by Xi Zou, Feb 24, 2002.

Francher, P., Ervin, R., Sayer, J., Hagan, M., Bogard, S., Bareket, Z., Mefford, M., Haugan, J., 1998. Intelligent cruise control field operational test: final report, July 1998. DOT HS 808 849. NTIS, Springfield, Virginia 22161, USA.

Gipps, P. G., 1981. A behavioural car-following model for computer simulation, Transportation Research, vol. 15B, pp 105-111,1981.

HIDO (2001), HIDO website: http://www.hido.or.jp/ITSHP_e/wi/cont_wi4.htm, accessed by Xi Zou, Feb 24, 2002.

Holve, R., Protzel, P., Bernasch, J., Naab, K.,(1995a) Adaptive Fuzzy Control for Driver Assistance in Car-Following, Proceedings of the 3rd European Congress on Intelligent Techniques and Soft Computing - EUFIT '95. Aachen, Germany, Aug., pp. 1149 - 1153.

Holve, R., Protzel, P., Naab, K., (1995b). Generating Fuzzy Rules for the Acceleration Control of an Adaptive Cruise Control System, Proceedings and at the NAFIPS conference, being held June19th-22nd, 1995 in Berkeley, CA, USA.

Ioannou, P. A., Ahmed-Zaid, F., Wuh, D. H., (1994). A Time Headway Autonomous Intelligent Cruise Controller: Design and Simulation, California PATH Working Paper UCB-ITS-PWP-94-07, April.

ISA (2001), Auto cruise control morphs, ISA Intech.Online website: http://www.isa.org/journals/intech/brief/1,1161,579,00.html, 05 March, accessed by Xi Zou, Feb 24, 2002.

Ivsource.net (2000). Finally! Adaptive Cruise Control Arrives in the USA, http://ivsource.net/archivep/2000/sep/a000929_USacc.html, Ivsource.net and

Richard Bishop Consulting (RBC) copyright, September 29, accessed by Xi Zou in Feb 24, 2002.

Jones, Willie D. (2001), Keeping Cars from Crashing, IEEE Spectrum Online, Sept. http://www.spectrum.ieee.org/WEBONLY/publicfeature/sep01/intel.html, accessed by Xi Zou, Feb 24, 2002.

Koppa, Rodger J., 1998. Chapter 3: Human factor, Monograph of Traffic Flow Theory, pp 3-15, 1998.

Koziol, J. et al., (1999), Evaluation of the Intelligent Cruise Control System Volume I – Study Results, DOT-VNTSC-NHTSA-98-3, DOT HS 808 969 Final Report, October.

Kuhne R. and Michalopoulos, P. (2001) Contimuum flow models. In Gartner, N.H., Messer, C., and Rathi, A.K., editors, Traffic Flow Theory, chapter 5. http://www.tfhrc.gov/its/tft/tft.htm, accessed by Xi Zou, Feb 24, 2002.

Li, P. Y. and Shrivastava, A. Traffic flow stability induced by constant time headway policy for adaptive cruise control (ACC) vehicles Transportation Research - Part C: Emerging Technologies. (accepted for publication)

Liang, Chi-Ying and Peng, H., (1999) Optimal Adaptive Cruise Control with Guaranteed String Stability, Vehicle System Dynamics, Vol.32, No.4-5, November, pp.313-330.

Liang, Chi-Ying and Peng, H., (2000). String Stability Analysis of Adaptive Cruise Controlled Vehicles, JSME International Journal Series C, Volume 43, No.3, September , pp.671-677.

Lighthill, M.J. and Whitham, G.B. (1955). On kinematic wave II: A theory of traffic flow on long crowded roads. Proceedings of the Royal Society of London, A229: 317-345.

Marsden, Greg, McDonald, Mike and Brackstone, Mark, 2001.Towards an understanding of adaptive cruise control, Volume 9, Issue 1, Pages 33-51, Transportation Research Part C: Emerging Technologies, February 2001.

Mason, Anthony D. and Woods, Andrew W., 1997 .Car-Following Model of Multispecies Systems of Road Traffic, Physical Review E March 1997 Volume 55, Number 3.

McDonald, Mike (2001), Deployment of Inter-urban Advanced Transport Telematics Test Scenarios, DIATS web site:http://europa.eu.int/comm/transport/extra/diatsia.html, accessed by Xi Zou, Feb 24, 2002.

Minderhoud, M.M., Bovy, P.H.L., 1998. Impact of intelligent cruise control strategies and equipment rate on road capacity. In: Proceedings of the Fifth Annual World Congress on ITS, Korea.

Murray, R. M., Li, Z., and Sastry, S. S. (1994). A Mathematical Introduction to Robotic Manipulation, pp43-44, CRC Press LLC, March.

Nagel, K. Shreckenberg, M. (1992). A cellular automaton model for freeway traffic. Journal of Physics I, France, 2: 2221-2229, 1992.

Newell, G.G. (1982). Application of queuing theory, Chapman and Hall, 2nd edition.

NHTSA (2000), Final Report -- Automotive Collision Avoidance System (ACAS) Program, DOT HS 809 080, August.

Nice, Karim (2001), How Cruise Control Systems Work, http:/www.howstuffworks.com/cruise-control.htm/printable, accessed by Xi Zou, Feb 24, 2002.

Nilsson, L., (1995). Safety effects of adaptive cruise control in critical traffic situations. In: Proceedings of the Second World Congress on ITS. Yokohama, Japan.

Nissan, (1998). SUPPLEMENTAL NISSAN NEWS, Corporate Communication Dept. A30-SN-8089, http://www.nissan-global.com/GCC/Japan/NEWS/25c6.htm, November 25, accessed by Xi Zou, Feb 24, 2002.

NTSB (2001), NTSB Recommends Collision Warning Systems For New Commercial Vehicles, SB-01-10, May 1, http://www.ntsb.gov/Pressrel/2001/010501.htm, accessed by Xi Zou, Feb 24, 2002.

Patterson, A. K., (1998) Intelligent Cruise Control System Impact Analysis, Thesis of the Virginia Polytechnic Institute and State University, August 6.

Phil Barber, (2001). Jaguar website: Transport management - Adaptive Cruise Control, http://www.acea.be/acea/um/JaguarAdaptive.html, accessed by Xi Zou, Feb 24, 2002.

Press, William H., Teukolsky, Saul A., Vetterling, William T., Flannery, Brian P., 1992. Numerical Recipes in C: The Art of Scientific Computing, Second Edition, Cambridge University Press, 1992.

Prigogine, I. And Herman, R. (1971). Kenitic theory of vehicle traffic. NewYork: American Elsevier.

Rothery, R. W. (2000). Car following models. In Gartner, N.H., Messer, C., and Rathi, A.K., editors, Traffic flow theory, chapter 4. http://www.tfhrc.gov/its/tft/tft.htm, accessed by Xi Zou, Feb 24, 2002.

Shrivastava, Ankur and Li, Perry Y., 2000. Traffic flow stability induced by constant time headway policy for adaptive cruise control (ACC) vehicles, Proceedings of the American Control Conference, June, 2000, pp 1503-1508.

Swaroop, D., Huandra, R., (1999). Intelligent Cruise Control System Design Based on a Traffic Flow Specification, UCB-ITS-PRR-99-5, California PATH Research Report, February.

Tier One (2001a), ACC Market &Technology – Excerpt, webpage: http://www.tierone.com/accmtrexcerpt.html, accessed by Xi Zou, Feb 24, 2002.

Tier One (2001b), Market for Automotive Adaptive Cruise Control to Soar in Coming Decade; TIER ONE Report Projects Huge Increase in Installation Rate, to $2.4B Annually, http://www.tierone.com/accmtrpr.html, accessed by Xi Zou, Feb 24, 2002.

Van Arem, B., Hogema, J., Smulders, S., 1996. The impact of autonomous intelligent cruise control on traffic flow. In: Proceedings of the Third Annual World Congress on ITS. Orlando, FL, USA.

VanderWerf, J., Steven, E., Miller, M. A., Kourjanskaia N., (2001). Evaluation of the Effects of Adaptive Cruise Control Systems on Highway Traffic Flow Capacity and Implications for Deployment of Future Automated Systems, 81st Annual Meeting of TRB.

Visteon (2001), Portfolio -Product Name: Adaptive Cruise Control, http://www.visteon.com/technology/automotive/dri_acc.html, accessed by Xi Zou, Feb 24, 2002.

Wang, J.M. and Rajamani, R., 2001. Should Adaptive Cruise Control (ACC) Systems be Designed to Maintain a Constant Time-Gap between Vehicles? Draft.

Wu, J., McDonald, M., Brackstone, M., 1998. A fuzzy logic microscopic simulation model for interurban ATT assessment. In: Proceedings of the 10th European Simulation Symposium and Exhibition. Society for Computer Simulation International ISBN 1-56555-154-0, Nottingham, UK.

Zou, X. and Levinson, D., (2001) CRITERION FUNCTION OF TRAFFIC FLOW PATTERNS, submitted to World Congress of ITS 2002.