

## CHAPTER 2

### LITERATURE REVIEW

The behavior of a vehicle following another vehicle determines, on the one hand, the capacity of a roadway section, while the reaction of drivers to unexpected events (or the lack thereof), on the other hand, determines the occurrence of collisions.

The Intelligent Vehicle Initiative (IVI) provides vehicle-based tools that could assist drivers in reacting both more rapidly and effectively to a range of external stimuli. Intelligent or adaptive cruise control systems (ICC or ACC), for example, attempt to assist drivers in better maintaining a safe headway under normal driving conditions. In addition, automatic braking systems may provide additional safety benefits by assisting drivers to respond more quickly to unexpected events.

The focus of this chapter is to describe the research that has been conducted to date in order to evaluate the safety impacts of ACC type of control. Initially, the various types of ICC systems that have been described in the literature to date are presented. The intent of this overview is to demonstrate that the term ICC or ACC may differ depending on the source of information. For example, some ACC systems have no braking capabilities while others do. Consequently, results need to be interpreted within this context.

Following a description of the various types of ACC applications, this chapter synthesizes the results of evaluation studies of these ACC systems. The intent of this synthesis is to describe what has been done so far in the area of evaluating ACC type of control in order to set the stage for the subsequent chapters that describe how ACC was evaluated in this thesis.

As mentioned earlier ACC systems can alter vehicle car-following behavior in addition to the potential for an accident. Consequently, this chapter also synthesizes the literature of car-following models in order to demonstrate how the work that is presented in this thesis differs from what has been done to date. Furthermore, this chapter describes the state-of-the-art work in the area of safety impacts of ACC type of control.

## **2.1 Intelligent/Adaptive Cruise Control Systems**

As indicated in the introduction, the focus of this chapter is the impact of ICC vehicle control. It is important to understand what ICC is and how ICC is different from vehicles currently operated on the road. The first topics of this section, therefore, are conventional cruise control (CCC) usage and a contrast of CCC and ICC capabilities. The remaining sub-sections describe general configurations of developed ICC systems as well as provide additional information on three components of ICC systems: target sensor, vehicle control strategies and the vehicle-driver interface.

### *2.1.1 Intelligent and Conventional Cruise Control Operation*

As indicated above, the purpose of the following paragraphs is to describe CCC usage as well as compare CCC and ICC capabilities. Figure 2-1 illustrates a cruise control layout.

**Conventional Cruise Control.** Conventional cruise control takes over the accelerator operation at speeds over 48 km/h (30 mph) when it is engaged. Activation requires that the ON button is pressed and the desired speed set. The driver has to press the ON button to activate the system each time the engine is started. Once the cruise control is ON, the driver can set a speed by driving at the desired speed and then pressing the SET button.

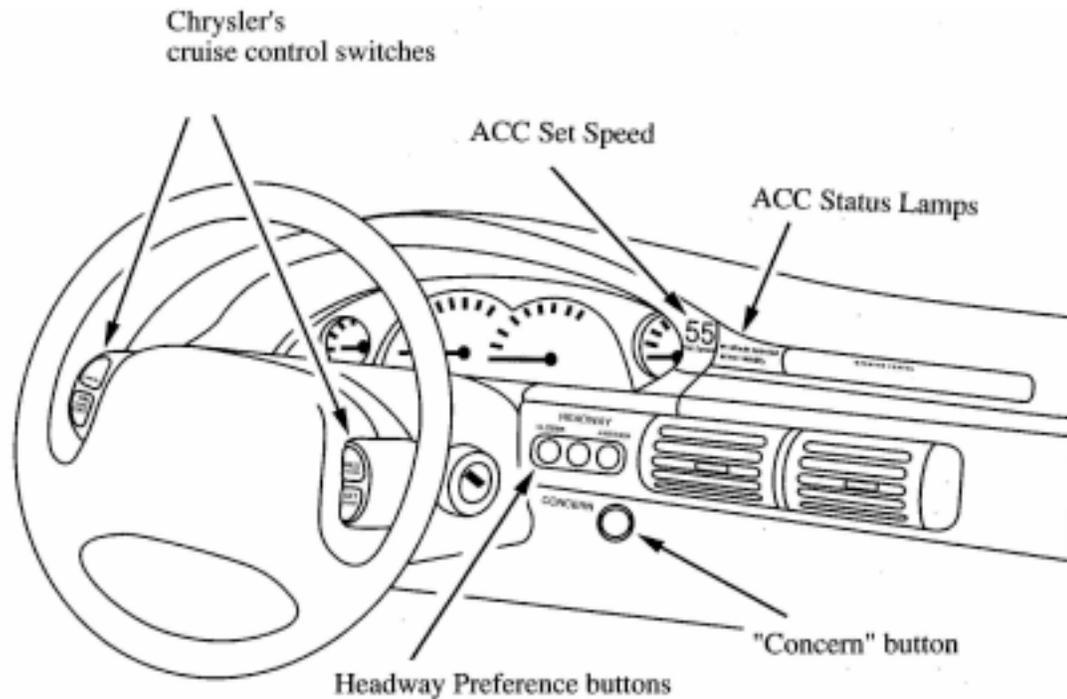
In order to deactivate the system while maintaining the set speed in memory, the driver has the choice to either make a soft tap on the brake pedal or press the CANCEL button. Pressing the OFF button or turning off the ignition turns the speed control system off and erases the memory.

In order to resume to a previously set speed, the driver needs only to press the RESUME button as long as the speed exceeds 40 km/h (25 mph). The driver can also vary the speed setting by either pressing and holding the ACCEL button and releasing the button when the new set speed is established, or by tapping the ACCEL button. Each tapping of the ACCEL button results in a 3.2 km/h (2 mph) increase in the vehicle speed.

In order to decrease the speed while the speed control is ON, the driver needs to hold the COAST button and release it when the desired speed is reached.

It must be noted that pressing the accelerator does not alter the set speed. Consequently, when the accelerator pedal is released, the vehicle returns to the previously set speed. In addition, the conventional cruise control can downshift to third gear if it is necessary to maintain the vehicles set speed.

**Intelligent Cruise Control.** While conventional cruise control (CCC) maintains a fixed vehicle speed during operation, the idea of the ICC system is to maintain a chosen headway distance (Martin 1995, 83). The operation of ICC is not always different, however, from CCC. While not in traffic, the ICC system acts as a CCC system (Koziol and Inman 1997, 146). The ICC system can downshift in order to maintain a selected headway or to maintain a set speed as is the case of conventional cruise control. The intent of the ICC system is that the number of times that a driver engages, disengages or changes the cruise control settings while in traffic decreases compared to CCC (Koziol and Inman 1997, 145).



**Figure 2-1 Chrysler Autonomous Cruise Control System Interface**

Source: ICC Field Operational Test Study Plan (Robinson et al., 1997).

### 2.1.2 Intelligent Cruise Control System Configuration

The following paragraphs describe the equipment used in the Mitsubishi ICC system and the signal parameters used in operation and evaluation of the Chrysler Concorde ICC system. It is important to note that ICC does not require equipment on adjacent vehicles (Palmquist 1993, 56) so the ICC system components described below are contained within a single vehicle.

**Mitsubishi System.** This system uses laser radar for the determination of vehicle position. Other components are the camera, vehicle speed sensor, steering angle sensor, throttle opening sensor, controller, throttle actuator and the automatic transmission control. The camera is used for lane determination purposes and is

located with the rearview mirror. The controller, located in the trunk, processes the data received from the speed sensor, the steering angle sensor and the throttle sensor. It determines the vehicle to follow and controls both the throttle actuator and the automatic transmission control based upon the calculated desired speed (Watanabe et al. 1995, 1229).

**Chrysler Field Operational Test System.** The results presented in this thesis are based upon a Field Operational Test (FOT) which uses ten 1996 Chrysler Concorde sedans equipped with ICC systems. The implemented Intelligent Cruise Control system uses the following signal parameters for evaluation and performance purposes (Fancher and others 1997, 156):

- $V_p$  = Velocity of the preceding vehicle
- $T_h$  = The ACC system's headway time setting
- $R$  = Range from the front of the following vehicle to the rear of the preceding vehicle
- $R_{dot}$  = Time rate of change of range; relative velocity between the two vehicles ( $R_{dot} = V_p - V$ )
- $V_c$  = An output of the headway control unit; velocity command to the engine controller
- $Shift$  = An output of the headway control unit; shift command to the transmission controller
- $\delta$  = Percent of full throttle position
- $V$  = Velocity of the following vehicle
- $V_{dot}$  = Acceleration (including deceleration) of the following vehicle
- $V_{set}$  = The driver's desired velocity when the road is clear; the speed set by the driver
- $R_h$  = The desired headway distance determined by  $T_h$  and  $V_p$  ( $R_h = T_h * V_p$ )

### 2.1.3 Description of Intelligent Cruise Control Sub-Systems

While a general description of the ICC system is given above, details of target sensing, vehicle control strategies, and the driver-ICC interface are provided below.

**Target Sensor.** Vehicles in front of the ICC equipped vehicle need to be detected. Palmquist (1993) suggests that “ideally three lanes should be covered at a range of, say, 150 meters”. The target vehicle is the closest preceding vehicle in the same lane as the ICC equipped vehicle (Watanabe et al. 1995, 1230). Detection of surrounding vehicles is achieved with the use of infrared and/or radar sensors and also a camera. The scanning type radar measures distance and velocity vector using elapsed time information (Watanabe et al. 1995, 1230). The camera is used to determine the current travel lane of the ICC equipped vehicle and if surrounding objects are within the same lane (Watanabe et al. 1995, 1230).

**Vehicle Control.** There are a multiple number of control strategies that are used by the equipped ICC vehicle. The strategy in use depends upon the set cruise speed and headway as well as the velocity of and distance to the target vehicle (Palmquist 1993, 57). The functions of the ICC system as seen by the Mitsubishi Corporation for various driving scenarios are described next (Watanabe et al. 1995, 1231). Where there is no target vehicle the speed of the vehicle under control is that set by the driver. This is equivalent to the conventional cruise control operation. When a target vehicle is introduced, the speed is adjusted in order to maintain a preset headway selection. If the approach to the target vehicle is at a low relative speed, throttle and downshifting are controlled by the ICC system in order to maintain the desired headway distance. If the approach is at a high relative speed an additional audible warning is given to the driver to start braking. Once the driver starts braking the system control is cancelled. If the target vehicle is accelerating then the follower vehicle can accelerate to the preset speed while maintaining the desired headway. If

the target vehicle disappears, then the follower vehicle can accelerate to the preset speed without headway concern.

**Driver Interface.** Using a system similar to conventional cruise control the typical operations of turning on and off the system, setting cruise speed, increasing and decreasing the set speed value, and resuming an already selected speed can be achieved. As with conventional cruise control, the use of the brake by the driver at any time cancels the Intelligent Cruise Control operation (Palmquist 1993, 57). Since there is the added headway component it is important that the driver not be confused about the system status (Palmquist 1993, 57). The Intelligent Cruise Control display of the Mitsubishi system incorporates a center message display which shows the speed set by the driver, headway distance, control status and issues a warning when required (Watanabe et al. 1995, 1233).

## 2.2 Evaluations of ICC Systems

As indicated in the introduction the focus of this chapter is to describe research that has evaluated the safety impacts of ICC systems. This section explores five ICC system studies including highway, simulator and accident report analysis.

Specifically, this section describes two Mitsubishi highway tests, the Swedish Road and Transport Research Institute VTI Simulator study, the University of Michigan Transportation Research Institute ACC baseline system test study, and a hypothetical ICC system accident report study and platoon simulation.

### 2.2.1 Mitsubishi Vehicle Tests

The Mitsubishi Motor Corporation conducted vehicle tests considering the effects of ICC on headway distance distribution and driving load (Watanabe et al. 1995, 1234-1235). Unfortunately, Watanabe et al. (1995) did not include a detailed description of the test methods or specific numerical results in this paper but the general results that were presented are given next.

**Time Distribution of Headway.** The headway distance test considered a vehicle following a target vehicle on a highway at speeds 80 to 100 km/h (Watanabe et al. 1995, 1234). It was found that the use of ICC reduced the variability of headway compared to a vehicle without cruise control (Watanabe et al. 1995, 1234). Further, it was found that vehicles without control occasionally experienced headways under 25 m (Watanabe et al. 1995, 1234).

**Driver Workload.** This test compared the frequency of operations of the accelerator pedal, acceleration/deceleration cruise control switch, brake pedal and resume button between ICC and CCC use. The results of the testing indicated a reduction in the frequency of driver operations with the ICC system (Watanabe et al., 1235). The results are summarized in Table 2-1.

**Table 2-1 Mitsubishi Driving Load Test Results**

Operation	Conventional Cruise Control	Intelligent Cruise Control
Acceleration Pedal	12	3
Accel/Decel Switch	85	1
Brake Pedal	18	4
Resume	21	4

Source: Development of an Intelligent Cruise Control System (Watanabe et al., 1995)

### 2.2.2 *University of Michigan Transportation Research Institute Autonomous Cruise Control Baseline System Test Study*

In this section the University of Michigan Transportation Research Institute (UMTRI) Autonomous Cruise Control (ACC) baseline study is briefly described including some results of the test study. The study used balanced groups with respect to gender, age and cruise control experience. A total of 36 drivers participated in the study each driving an 88 km (55 mile) route during off-peak hours (Fancher and others 1995, 1734). The control algorithm of the ACC system was based upon range, range rate, vehicle tracking, set speed and vehicle speed. The distance sensor was capable of tracking objects within 2 – 160 m of the test vehicle. Stationary objects were not considered as targets. The headway was controlled by throttle only (no brake action by the ACC system). This resulted in a maximum deceleration of approximately 0.05g (Fancher and others 1995, 1733).

Each participant completed surveys regarding the test.

“Subjects frequently responded that cruise control was useful in reducing driver workload, helping to maintain posted speed limits, and resulted in better gas mileage than manual control. However, some subjects expressed concern with becoming too dependent on cruise control, and ACC in particular” (Fancher and others 1995, 1735).

Both velocity and braking behavior of all participants were analyzed. Only velocities greater than or equal to 88.5 km/h (55 mph) were considered. The mean velocity of the ACC mode was 104.2 km/h (95.1 fps), the CCC mode 104.6 km/h (95.5 fps) and for the no cruise control mode was 106.5 km/h (97.2 fps). No statistical significance was found for mean velocity between the three modes of operation. The mean number of brake applications was determined for each driver. This produced a statistical significant difference (Fancher and others 1995, 1736). The mean number of brake applications for the manual condition was 5.8, the CCC tests 11.3, and for the ACC situations were 7.4.

The results obtained in the study were used to determine areas where ACC might improve safety. These areas relate to time available for driver response, perception of relative velocity and accelerator pedal movement. (The “time available for driver response” is the time left, after the driver has first reacted to a stimulus, before a collision occurs). The baseline value of time available for driver response supported by the ACC system was 1.4 seconds which is larger than the time available for response of average drivers (Fancher and others 1995, 1737). This increase in time available for driver response gives more time for the driver to decelerate potentially reducing the relative velocity of two vehicles and therefore could mean a reduction in the number of rear-end collisions as well as reduction in the severity of accidents (Fancher and others 1995, 1737). In addition to available response time benefits, ACC may benefit with respect to relative velocity detection. The ACC system was more responsive to relative velocity than the human driver so the approach of an ACC equipped vehicle to preceding vehicles may be much more “orderly and consistent” (Fancher and others 1995, 1738). The last area of potential benefit considered in this study was driver effort and accelerator pedal use.

“Drivers tend to be moving the accelerator pedal continuously with a ratio of standard deviation to the mean of approximately 0.43 at highway speeds. To the extent that the benefits of removing this effort (and all of the associated neurological decisions to increase or decrease speed), greatly reduces the driver’s work, the ACC system leads to safer as well as more pleasant driving” (Fancher and others 1995, 1738).

Both UMTRI and the Mitsubishi Motor Corporation recognized the potential reduction in driver workload with respect to brake applications and accelerator pedal movements. Specific numeric results were not presented for the Mitsubishi tests but UMTRI did find a significant difference in the mean number of brake applications per driver.

### 2.2.3 Swedish Road and Transport Research Institute VTI Simulator Study

In contrast to the two previous sections, the Swedish Road and Transport Research Institute used a simulator for their study. This section briefly describes the simulator test performed by the Swedish Road and Transport Research Institute and its results. Ten male and ten female experienced drivers between 26 and 46 years of age took part in the study. One half of the group (equal female and male participants) performed the test with ACC and the other half performed the test manually. The ACC system prototype used controlled speed and distance with the use of throttle and brake. The maximum braking capabilities of the ACC system were  $2 - 3 \text{ m/s}^2$ . The full ACC system could be active at speeds of 30 – 130 km/h. At higher speeds the system worked as a CCC system while at lower speeds the system shut off. The display for the system included an amber car symbol when sensors detected a lead vehicle. The system did not, however, recognize stationary objects as a lead vehicle (Nilsson 1995, 1255). The simulated 2-lane roadway had a designated speed limit of 110 kilometers per hour and a length of 100 kilometers (Nilsson 1995, 1255).

Three traffic situations were modeled for this study. Each required driver intervention even with the activation of ACC. The first situation investigated the impact of hard braking lead vehicles. In this case, the subject vehicle was trapped behind the lead vehicle (due to another vehicle passing the subject vehicle) when the lead vehicle braked at  $8 \text{ m/s}^2$  (Nilsson 1995, 1256). The maximum braking capabilities of the ACC system were insufficient and an acoustic signal (tone) indicated that the subject was required to take control. Nine out of ten of the ACC subject drivers received the warning from the ACC system. No statistical difference (5%) was found between the ACC drivers and the manual drivers with respect to reaction time. The time difference between the lead vehicle brake lights to the time that the driver activated the brakes was on average 1.33 seconds for the ACC driver and 1.49 seconds for the manual driver (Nilsson 1995, 1256).

The second situation involved the subject vehicle passing a vehicle and having a car pull out in front of the subject vehicle. Once again, the maximum braking for of the ACC system was insufficient to avoid collision. In this case, all test drivers would brake immediately. The time between the left direction indicator activation and the braking action was on average 1.11 seconds for the “ACC drivers” and 1.17 seconds for the manual drivers (Nilsson 1995, 1256). No warnings were issued by the ACC system since all subjects took immediate control over the vehicle. No statistical difference (5%) was found between the ACC and non-control users (Nilsson 1995, 1256).

The third and final situation had the subject vehicle approach a stationary queue. The queue covered both lanes and since the ACC system did not detect stationary vehicles as lead vehicles all response to the queue was manual. A total of 5 collisions were observed in this test situation. Four resulted from the ACC supported drivers, one from the group without any ACC support (Nilsson 1995, 1256). Each driver rated six workload factors (NASA-RTLX workload factors) after completing the simulator session (Nilsson 1995, 1257). There were no statistically significant differences (5%) between the responses of the subjects with and without ACC (Nilsson 1995, 1258). Therefore, the greater number of collisions for the ACC users in this case can not be explained by an increase in perceived driver workload (Nilsson 1995, 1259).

The mean minimum time headway was calculated for each critical traffic situation described above. The mean minimum time headway for no collision in the stationary queue critical situation was calculated as well. The results are presented below in Table 2-2. The use of ACC resulted in a shorter mean minimum time headway for the stationary queue situation. The other two situations, however, had longer minimum time headways for ACC usage. The most variability between drivers was

observed for the stationary queue situation and the least variability for the car pulling out situation.

**Table 2-2 Minimum Time Headway (seconds) for Critical Traffic Situations**

Situation	ACC		Manual	
	Mean	Standard Deviation	Mean	Standard Deviation
Cars Braking Hard	1.13	0.55	1.07	0.75
Car Pulling Out	0.49	0.05	0.48	0.08
Stationary Queue	1.19	1.11	2.10	1.01
Mean for no Collision	1.98		2.33	

Source: Safety Effects of Adaptive Cruise Controls in Critical Traffic Situations (Nilsson, 1995)

Nilsson (1995) included results regarding braking as well. The time headway when braking was started, the maximum braking force, the deceleration rate when maximum braking forces were applied and the time headway when the maximum braking forces were applied were observed. Table 2-3 indicates that drivers using ACC in two out of three critical situations started braking at a shorter time headway than the drivers without ACC. The differences were not significant (5%) (Nilsson 1995).

**Table 2-3 Time Headway (seconds) at Start of Braking for Critical Traffic Situations**

Situation	ACC		Manual	
	Mean	Standard Deviation	Mean	Standard Deviation
Cars Braking Hard	1.62	0.32	1.70	0.57
Car Pulling Out	0.57	0.06	0.52	0.09
Stationary Queue	2.79	0.70	3.38	0.86

Source: Safety Effects of Adaptive Cruise Controls in Critical Traffic Situations (Nilsson, 1995)

The mean maximum braking forces applied for each critical traffic situation studied are shown in Table 2-4.

**Table 2-4 Maximum Braking Forces Applied (Newton) for Critical Traffic Situations**

Situation	ACC		Manual	
	Mean	Standard Deviation	Mean	Standard Deviation
Cars Braking Hard	248	78	297	172
Car Pulling Out	119	49	94	42
Stationary Queue	358	49	302	120
Mean for no Collision	360		286	

Source: Safety Effects of Adaptive Cruise Controls in Critical Traffic Situations (Nilsson, 1995)

The manual drivers in the cars braking hard situation had higher braking forces than the ACC drivers. The ACC drivers, however, had higher braking forces in the stationary queue situation. There was an even greater difference between the means for the no collision stationary queue situation. The deceleration at maximum braking forces are shown next in Table 2-5.

**Table 2-5 Deceleration (m/s<sup>2</sup>) at Maximum Braking Forces for Critical Traffic Situations**

Situation	ACC		Manual	
	Mean	Standard Deviation	Mean	Standard Deviation
Cars Braking Hard	7.78	1.9	7.33	2.23
Car Pulling Out	7.08	1.27	5.13	0.94
Stationary Queue	8.67	0.23	7.70	1.15
Mean for no Collision	8.58		7.61	

Source: Safety Effects of Adaptive Cruise Controls in Critical Traffic Situations (Nilsson, 1995)

The largest mean deceleration was applied by the ACC users in the stationary queue situation while the lowest deceleration was applied by the manual users in the car pulling out situation. The time headways at maximum braking forces are given next in Table 2-6.

**Table 2-6 Time Headway at Maximum Braking Forces for Critical Traffic Situations**

Situation	ACC		Manual	
	Mean	Standard Deviation	Mean	Standard Deviation
Cars Braking Hard	1.34	1.03	1.20	0.74
Car Pulling Out	0.49	0.05	0.48	0.08
Stationary Queue	1.50	0.92	2.32	0.98
Mean for no Collision	2.17		2.52	

Source: Safety Effects of Adaptive Cruise Controls in Critical Traffic Situations (Nilsson, 1995)

The mean time headway at maximum braking for both the ACC and non ACC users in the car pulling out situation were identical to the minimum time headways shown in Table 2-2. For the approach to the stationary queue situation, the mean time headway at maximum braking was shorter for the ACC user compared to the manual driver. The opposite was true for the cars braking hard situation.

Overall it is seen that the different critical traffic situations produced varied behavior depending on the type of vehicle control. There was little impact between the reaction times for ACC and manual drivers for the lead vehicles braking hard situation. As previously mentioned, nine out of the ten ACC subject drivers received a warning from the ACC system. The second situation involved a car pulling out in front of the subject vehicle. The mean minimum time headways and variability of both ACC and manual drivers was the least for this situation. In fact the actions of the ACC and manual drivers were practically identical. The third and final situation

was the approach to a stationary queue. Of the five collisions observed in this test situation four resulted from the ACC supported drivers.

#### *2.2.4 Accident Analysis using a Hypothetical ICC System*

Chira-Chavala and Yoo (1993) evaluated potential safety benefits of a hypothetical intelligent cruise control system. The intelligent cruise control system was considered hypothetical since at the time there was no intelligent cruise control systems in use (Chira-Chavala and Yoo 1993, 136). The intelligent cruise control system was thought to reduce accidents due to changes in headway and reaction time. Since headway is maintained by the ICC system, “incidence of ‘excessive’ speeds for prevailing conditions and ‘tail-gating,’ which are commonly cited accident contributing factors, can be prevented or reduced” (Chira-Chavala and Yoo 1993, 137). Secondly, the response time of the system is faster than the driver reaction time (Chira-Chavala and Yoo 1993, 137). The study examined a total of 379 police accident reports from 4 Californian counties. This consisted of 118 fatal accident reports, 112 severe-injury reports and 149 visible-injury reports. Results indicated that 23 accidents might have responded with intervention from the hypothetical ICC system (Chira-Chavala and Yoo 1993, 138). The causes of these crashes were considered to be due to close following, slow reaction time, distraction from driving, misjudging speeds of slow moving vehicles at night, unaware of lead vehicles actions (slowing), excessive speed combined with night, and incorrect judgement of speed due to the influence of alcohol.

#### *2.2.5 Platoon Simulation*

Chira-Chavala and Yoo (1993) used vehicle simulation to determine the potential effects of a hypothetical ICC system on several traffic operation characteristics. This meant the modeling of two traffic streams: one with the use of ICC and the other under manual conditions. The procedure determined the speed, acceleration and

headway profiles of a traffic stream consisting of 10 vehicles. The lead vehicle followed a specific speed profile. When the lead vehicle changed speed, the following vehicles also changed their speed. The study concluded that ICC use would not cause traffic disturbance problems (Chira-Chavala and Yoo 1993, 146). A second conclusion was that ICC could improve driver comfort due to a reduction in frequencies of hard deceleration and acceleration. It was also suggested that ICC systems could “enhance speed harmonization among vehicles in the traffic stream” and would allow drivers to reach desired headways faster when responding to a disturbance ahead of them (Chira-Chavala and Yoo 1993, 146).

### **2.3 Car Following Models**

Car following models attempt to capture the microscopic characteristics of a vehicle in traffic. The occupied longitudinal space of a vehicle or, in other words, the distance headway (distance from one point on the lead vehicle to the same point on the follower vehicle) is obtained through these models. Since density is a measurement of vehicles per length of roadway, a car following model is a microscopic representation of density. The car following models presented here reflect several approaches to car following modeling. The first two models attempt to capture minimum safe headway only. The “driver model” determines the desired acceleration of drivers for both free flow and car following situations. Relative speed threshold is incorporated into the car following situation. The fourth description is of the General Motor’s models and stability research. The “five driving zones model” uses a double loop configuration where the purpose of one loop is to determine the desired speed of the vehicle and the other is to achieve this desired speed. Driver perception is divided into five different driving zones in this model. The last model is a linear acceleration model that includes driver perception, desired headway and a collision avoidance check.

### 2.3.1 Pipes' Model

Pipes defined the minimum safe distance headway ( $d_{MIN}$ ) as follows (May 1990, 146-147):

$$d_{MIN} = [x_n(t) - x_{n+1}(t)]_{MIN} = L_n \left[ \frac{x'_{n+1}(t)}{1.47*10} \right] + L_n \quad (1)$$

Where  $x_n(t)$  = position of the lead vehicle (ft) at time  $t$ ,

$x_{n+1}(t)$  = position of the following vehicle (ft) at time  $t$ ,

$L_n$  = length of the lead vehicle (ft), and

$x'_{n+1}(t)$  = speed of the following vehicle (ft/sec) at time  $t$ .

It is thought that the minimum safe distance headway increases linearly with speed.

The results obtained using the above model with a lead vehicle length of 21 to 22 feet are close to field measurements (May 1990, 165).

### 2.3.2 Forbes' Model

Forbes includes reaction time into the minimum safe time headway ( $h_{MIN}$ ) equation (May 1990, 166):

$$h_{MIN} = \Delta t + \frac{L_n}{x'_n(t)} \quad (2)$$

Where  $\Delta t$  = reaction time,

$L_n$  = length of the lead vehicle (ft), and

$x'_n(t)$  = speed of the lead vehicle (ft/s) at time  $t$ .

Representing the above as a safe minimum distance headway gives (May 1990, 166):

$$d_{MIN} = \Delta t [x'_n(t)] + L_n \quad (3)$$

May (1990) indicates that “there is a very close agreement between Forbes’ model and the field study results in the midspeed range”.

These first two models give insight into minimum safe distance headway only and no detail is provided for actual car following actions. Since May (1990) indicates that both provide close agreement to field study results there is no definite advantage of one equation over the other. While it is important to recognize the minimum safe distance headway, a violation of this headway does not imply that a collision is eminent. It is therefore important to develop a driver reaction model that provides insight into how minimum safe distance is reached and what occurs afterward. The remaining models in this section provide some insight into the car following situations.

### 2.3.3 *The Driver Model*

This model is divided into three sections: the free flow driver, the car following driver and driver perception. The free flow situation ensures that the driver maintains the desired speed while the car following situation keeps a desired headway while trying to match the speed of the lead vehicle. An additional perception component is added to the car following model to ensure that the driver does not react to a relative speed that the driver would not be able to perceive.

**Free Flow Driver Model.** In free flow conditions the driver tries to reach or maintain the desired speed within certain limits. Within what limits is the driver satisfied with the speed? Hogema (1998) uses a difference of three percent. Specifically, if the actual speed of the vehicle is more than three percent different from the desired speed then the desired acceleration is calculated. The following equation is used for desired acceleration determination (Hogema 1998, 3):

$$a_v(t) = K * [v(t') - v_{ref}] \quad (4)$$

Where  $t$  = time (s) of current simulation time step,

$t'$  = moment of the reaction time before the current time  $t$  (s),

$a_v(t)$  = desired acceleration ( $m/s^2$ ) at time  $t$  which must be within comfortable boundaries,

$v(t')$  = driver's speed (m/s) at time  $t'$ ,

$v_{ref}$  = driver's intended speed (m/s), and

$K$  = constant ( $s^{-1}$  with a typical value of 0.1).

Hogema (1998, 3) uses a time headway of 10 seconds as the limit between free flow and the car following situation.

**Car Following Driver Model.** In this situation the driver reacts to other vehicles present. The equation used by Hogema (1998) is based on the assumption that the driver will try and keep the relative speed to the lead car at zero while keeping the distance headway at a desired value:

$$a_f(t) = K_d * [D(t') - D_{ref}(t')] + K_v * v_{dif}(t') \quad (5)$$

Where  $t$  = time (s) of the current simulation time step,

$t'$  = moment of the reaction time before the current time  $t$  (s),

$a_f(t)$  = driver's intended acceleration at time  $t$ ,

$D(t')$  = actual following distance (m) at time  $t'$ ,

$D_{ref}(t')$  = driver's intended following distance (m) at time  $t'$ ,

$v_{dif}(t')$  = speed difference with respect to the lead car (m/s) at time  $t'$ , and

$K_d, K_v$  are constants ( $s^{-2}$  and  $s^{-1}$ , respectively).

The validity of representing  $K_d$  and  $K_v$  as constants was determined through experiment. What was found was approach situations with a time to collision less than 10 seconds had a larger  $K_v$  value inferring stronger reactions (Hogema 1998, 5). Therefore,  $K_v$  was found to vary and it is suggested that a separate sub-model describing approach behavior be developed (Hogema 1998, 5).

**Driver Perception.** Driver perception based upon relative speed is added to the basic model described in equation (5) above (Hogema 1998, 6):

$$v_t = D^2 * \frac{W_t}{W} \quad (6)$$

Where  $v_t$  = threshold (m/s),

$D$  = net following distance (m),

$w_t$  = angular velocity threshold (rad/s, typical value  $6E-4$ ), and

$W$  = width of the lead car (m).

### 2.3.4 The General Motors' Models

General Motors' researchers developed five levels of models each having the form that response (acceleration of the follower vehicle) is a function of both sensitivity and stimuli (relative velocity) (May 1990, 168). The "car following driver model" described above includes distance headway in addition to relative velocity. Distance headway is incorporated into the sensitivity term of the third, fourth and fifth General Motors' models. The complexity of the sensitivity term increases with each model level starting with a constant sensitivity for the first model and ending with velocity and distance headway components in the fifth model. The General Motors models are described next followed by a summary of the General Motors stability research where stability is a function of driver reaction time and the sensitivity term.

The first model equation is as follows (May 1990):

$$x''_{n+1}(t + \Delta t) = \alpha [x'_n(t) - x'_{n+1}(t)] \quad (7)$$

Where  $x''_{n+1}(t + \Delta t)$  = acceleration rate of the follower vehicle (ft/sec<sup>2</sup>) at time  $t + \Delta t$ ,

$[x'_n(t) - x'_{n+1}(t)]$  = relative velocity between lead and follower vehicles, and

$\alpha$  = sensitivity term assumed to be constant.

The second level equation uses one sensitivity value for close range ( $\alpha_1$ ) and another for when vehicles are far apart ( $\alpha_2$ ) (May 1990).

The third level equation incorporates distance headway into sensitivity resulting with (May 1990, 170):

$$x''_{n+1}(t+\Delta t) = \left[ \frac{\alpha_o}{x_n(t) - x_{n+1}(t)} \right] * [x'_n(t) - x'_{n+1}(t)] \quad (8)$$

Where  $\alpha_o$  = non-dimensionless constant (ft/s), and

$$(x_n(t) - x_{n+1}(t)) = \text{distance headway (ft) of lead and follower.}$$

The fourth model uses the speed of the follower in the sensitivity term. The purpose is to reflect the thought that an increase in traffic speed increases the follower's perception of relative velocity (May 1990, 170). The fourth model is represented as (May 1990, 170):

$$x''_{n+1}(t+\Delta t) = \left[ \frac{\alpha' * [x'_{n+1}(t + \Delta t)]}{x_n(t) - x_{n+1}(t)} \right] * [x'_n(t) - x'_{n+1}(t)] \quad (9)$$

Where  $\alpha'$  = dimensionless constant, and

$$[x'_{n+1}(t + \Delta t)] = \text{velocity of the follower (ft/sec) at time } t + \Delta t.$$

The fifth model generalizes the sensitivity term further by introducing exponents into the equation (May 1990, 171):

$$x''_{n+1}(t+\Delta t) = \left[ \frac{\alpha_{l,m} * [x'_{n+1}(t + \Delta t)]^m}{(x_n(t) - x_{n+1}(t))^l} \right] * [x'_n(t) - x'_{n+1}(t)] \quad (10)$$

**Stability Research.** As May (1990) indicates, unstable behavior is characterized by slow reaction time and over-response while stable behavior results from attentive driving with no sudden acceleration or decelerations. The limits for stable and unstable behavior were determined through General Motors research using the product (C) of reaction time ( $\Delta t$ ) and the sensitivity value ( $\alpha$ ) (May 1990, 179).

Local stability involves a pair of vehicles and results in three regions: non-oscillatory where C is less than 0.37, damped oscillatory where C is between 0.37 and 1.57, and increased oscillatory where C is greater than 1.57 (May 1990, 179-180). Asymptotic stability refers to a line of vehicles and is divided into two regions: damped

oscillatory where C is less than 0.5 and increased oscillatory where C is greater than 0.5 (May 1990, 179-180).

### 2.3.5 Five Driving Zones Model

The general form of the model described in this section has two main components: one is to determine the desired speed and the other is to adjust vehicle speed to achieve the desired speed. The previous models are concerned with the determination of the response acceleration but not the actual action. Perception is simplified to a one case scenario while in this model there are five driving zones based on driver perception.

**Driver Control Action.** The driver control action presented by Fancher and Bareket (1998) is based upon a sliding surface approach. This results in the following accelerator pedal position ( $\delta_t$ ) and brake pressure ( $P_b$ ) equations (Fancher and Bareket 1998, 2):

$$\delta_t = \left( \frac{mV}{P} \right) \left[ \frac{F_{drag}}{m} + \frac{V_c - V}{T_c} \right], 0 \leq \delta_t \leq 1 \quad \text{Acceleration} \quad (11)$$

$$P_b = \left( \frac{m}{K_b} \right) \left[ -\frac{F_{drag}}{m} - \frac{V_c - V}{T_c} \right], 0 \leq P_b \leq P_{bMAX} \quad \text{Deceleration} \quad (12)$$

Where m = mass of the vehicle,

V = velocity of the vehicle,

P = engine power of the vehicle,

$F_{drag}$  = drag forces on the vehicle,

$V_c$  = velocity command of the ACC controller,

$T_c$  = time constant in the ACC controller, and

$K_b$  = brake gain.

**Driver Perception Zones.** The determination of desired speed considers the driver's ability to perceive range and range rate. Fancher and Bareket (1998) identify five driving zones for a range versus range-rate perception space. The remainder of this section describes these five driving zones including the associated velocity equation where  $R$  = range to preceding vehicle,

$RL1$  = boundary for start of driver reaction,

$R_{\dot{}}$  = range rate of change,

$RL2$  = boundary for start of perception of range rate,

$R_h$  = desired range,

$V_c$  = velocity command of the ACC controller,

$V_{set}$  = driver's desired speed,

$V$  = velocity of the vehicle,

$T_2$  = time constant in the driver model for zone 2,

$T_3$  = time constant in the driver model for zone 3, and

$T_4$  = time constant in the driver model for zone 4.

Zone 1 is the situation where there are no preceding vehicles or the preceding vehicle is far enough away so to not affect headway control. Therefore the command velocity is the desired speed set by the driver:

$$V_c = V_{set} \quad (13)$$

Where  $R \geq RL1$ ,

$R_{\dot{}} < 0$ , and  
not in Zone 4.

In zone 4 the driver can perceive range rate which indicates a potentially critical situation. The upper boundary line of zone 4 is therefore determined by the perception constraint:

$$RL2 = R_{\dot{}} = -0.0005 * R^2 \quad (14)$$

The velocity equation tries to make the speed of the vehicle equal to the speed of the preceding vehicle. Once this is achieved then the control velocity can be used to ensure that range equals the desired range:

$$V_c = V + \frac{(R - R_h)}{T_4} + R_{dot} \quad (15)$$

Where  $R \leq RL2$ , and

$$R_{dot} < 0.$$

The command velocity equation for zone 4 has been used in a prototype Autonomous Cruise Control system for a field operational test (Fancher and Bareket 1998, 5).

Zone 2 represents a closing situation where the driver does not perceive range rate easily or quickly. Therefore range rate is not used in the determination of the command velocity.

$$V_c = V + \frac{(R - R_h)}{T_2} \quad (16)$$

Where  $R < RL1$ ,

not in Zone 4,

$R_{dot} < 0$ , and

not in Zone 5.

The boundary between zone 2 and zone 1 is the condition where the driver decides to start headway control if closing in from a long range. The slope of this line ( $T_{RL1}$ ) indicates that the driver has a feel for range rate by the observed changes in range (Fancher and Bareket 1998, 6). Both the range intercept and the slope of this boundary line are parameters to be found by field observation (Fancher and Bareket 1998, 6). The equation of this boundary line is as follows:

$$RL1 = R = 1.5R_h - T_{RL1} * R_{dot} \quad (17)$$

Zone 3 represents the increase in range case. The command velocity equation is similar to that of zone 2. The exception is the time constant which may differ since in zone 3 the driver is catching up to a faster vehicle instead of slowing down for a vehicle as in zone 2.

$$V_c = V + \frac{(R - R_h)}{T_3} \tag{18}$$

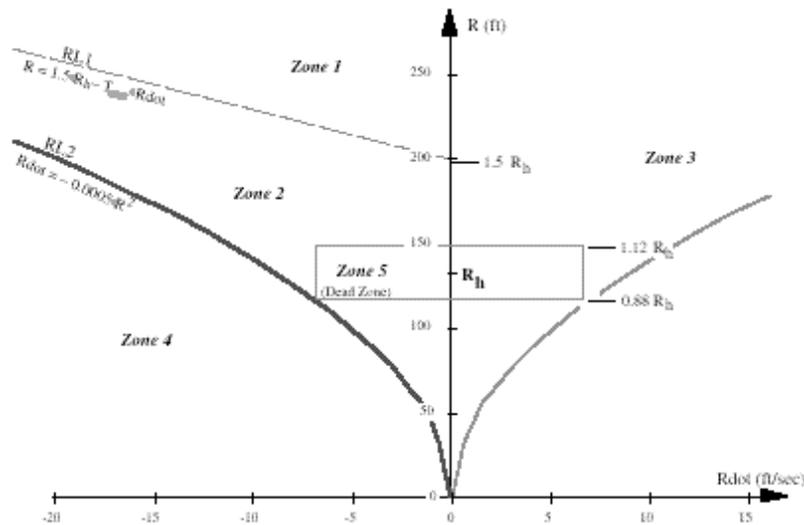
Where  $R_{\dot{d}} \geq 0$ , and  
not in Zone 5.

Zone 5 represents the dead zone in perception of range and the limited time constrained sensation of range rate (Fancher and Bareket 1998, 6). In this zone, the command velocity equals the current velocity.

$$V_c = V \tag{19}$$

Where  $R \leq 1.12 R_h$ ,  
 $R > 0.88 R_h$ ,  
 $R_{\dot{d}} < 0.0005 (0.88 R_h)^2$ , and  
 $R_{\dot{d}} > -0.0005 (0.88 R_h)^2$ .

Figure 2-2 is a range versus range rate plot that illustrates the five driving zones described above.



**Figure 2-2 Range Versus Range Rate Illustration of the Five Driving Zones Model**

Source: An Evolving Model for Studying Driver/Vehicle System Performance in the Longitudinal Control of Headway (Fancher and Bareket 1998).

### 2.3.6 Linear Acceleration Model

Aycin and Benekohal (1998) suggest the following for a longitudinal model used for real time and intelligent transportation system applications: make the model more realistic, consider more accurate brake reaction times and use a linear acceleration model instead of a constant and step wise function. A constant acceleration model gives a linear speed profile while the linear acceleration model gives a curvilinear speed profile. Aycin and Benekohal (1998) state that “field data shows that the speed profiles for stopping conditions are curvilinear”. The benefits of a linear acceleration model are continuous acceleration rates, solutions that are continuous in time, and that “the linear acceleration model best describes the driver behavior” (Aycin and Benekohal 1998, 2).

**Driver Perception.** Aycin and Benekohal (1998) incorporate perception thresholds and reaction time into the car following model. Driver reaction is based upon changes in speed, acceleration and headway. The perception threshold for approach speed is about (0.06\*average speed), the perception range for relative deceleration is about (0.5\*average deceleration rate of the vehicles), and the perception threshold for headway deviation is presented as (0.05\*average headway) (Aycin and Benekohal 1998, 5). Once any of the above thresholds is reached, driver reaction occurs after the brake reaction time. Therefore driver perception isn't incorporated into the command velocity as in the previous model, but is used for the purpose of identifying the start of the reaction time.

**Desired Headway.** It has been found that in car following a driver will try to maintain a desired headway by matching speed of the preceding vehicle (Aycin and Benekohal 1998, 5). In fact, this statement is found in the three previous models. The desired headway is incorporated into the car following model presented by Aycin and Benekohal (1998):

$$\text{Desired Headway} = \text{Speed} * \text{Preferred Time Headway} \quad (20)$$

Where preferred time headway is assumed to be independent of speed.

**The Model.** The model developed by Aycin and Benekohal does not consider lane changes or road sign influences. The maximum separation for a pair of vehicles to be considered in a car-following situation is 250 feet (Aycin and Benekohal 1998, 8).

The linear acceleration/deceleration model used is as follows (Aycin and Benekohal 1998, 8):

$$a_{t_1} = a_{t_0} + s * T \quad (21)$$

$$\int_{t_0}^{t_1} (v)_t dT = (x)_{t_1} = (x)_{t_0} + (v)_{t_0} * T + 0.5 * (a)_{t_0} * T^2 + 0.167 * s * T^3 \quad (22)$$

$$\int_{t_0}^{t_1} (a)_t dT = (v)_{t_1} = (v)_{t_0} + (a)_{t_0} * T + 0.5 * s * T^2 \quad (23)$$

Where a = acceleration,

s = acceleration rate (slope),

v = speed,

x = position,

t<sub>1</sub>, t<sub>0</sub> = final and initial states respectively, and

T = time interval.

The general equation for the desired headway of the follower is:

$$(d_p)_{t_1} = \Delta x - \Delta V * T - 0.5 * \Delta a * T^2 - 0.167 * s_f * T^3 \quad (24)$$

Where t<sub>0</sub> = present or initial time,

t<sub>1</sub> = future time when steady-state condition is achieved,

Δx = initial separation between the vehicles,

d<sub>p</sub> = desired spacing of the follower,

x<sub>f</sub>, x<sub>l</sub> = position of the follower and the leader,

L = length of the leading vehicle,

v<sub>f</sub>, v<sub>l</sub> = velocity of the follower and the leader,

a<sub>f</sub>, a<sub>l</sub> = acceleration of the follower and the leader,

$s_f$  = slope of the follower's acceleration (jerk),

$$\Delta x = (x_l - x_f)_{t_0} - L,$$

$$\Delta V = v_f - v_l,$$

$$\Delta a = a_f - a_l, \text{ and}$$

$$T = t_1 - t_0.$$

The general equation is solved considering that the velocity of the leader and the follower at steady state are equal in order to obtain an equation for the slope of the follower's acceleration. In addition the expression for the desired headway of the follower at steady state is found. Using both of these equations the following is obtained:

$$A * T^2 + B * T + C = 0 \tag{25}$$

$$A = 0.166 * \Delta a$$

$$B = 0.666 * \Delta V + a_l * t_p$$

$$C = -\Delta x + v_l * t_p$$

Where  $t_p$  = the preferred time headway.

“If we solve the equation for time  $t = t_0$ , the resultant slope value must be applied starting from that time. However, if there is a brake reaction time,  $t_b$ , this slope can not be applied before the end of the brake reaction time. Therefore, the principal equation is written for the time  $t = t_0 + t_b$  and only the resultant slope ( $s_f$ ) needs to be applied” (Aycin and Benekohal 1998, 11).

$$(a_f)_{t_1} = (a_f)_{t_0+t_b} + s_f * (t_1 - t_0 - t_b) \tag{26}$$

The critical solution where two positive roots are found is the smallest positive root. There are cases where the determinant is positive but both roots are negative and cases where the determinant is negative. For the case where the determinant is positive but both roots are negative if the smallest root is less than the brake reaction time ( $t_b$ ) then the follower reaches the desired state within the brake reaction time. In all other cases the car-following equation can not be applied and the solution is found according the relative velocity, relative acceleration and the acceleration of the leader

(p.14). The case where the determinant is less than zero is solved using a simpler constant acceleration model (Aycin and Benekohal 1998, 13).

$$(d_p)_{t_1} = \Delta x - (\Delta V)_{t_0+t_b} * T - 0.5 * \Delta a' * T^2 \quad (27)$$

$$T = \frac{(\Delta x - v_1 * t_p)}{(0.5 * \Delta V + a_1 * t_p)} \quad (28)$$

**Collision Avoidance Check.** The time to reach steady state is compared to the time to bring the leader to a complete stop at the leader's present rate of deceleration. The distance at which the follower must stop ( $d_f$ ) is as follows:

$$d_f = d_b + d_l - d_{buff} \quad (29)$$

Where  $d_b$  = spacing of vehicles after the reaction time,

$d_l$  = distance it takes the leader to stop, and

$d_{buff}$  = buffer space.

The time to stop the follower is then

$$t_f = 2 * \frac{d_f}{v_f} \quad (30)$$

If this time found from the equation above is less than the time to steady state obtained from the car-following equation, then another deceleration rate is required and is found from (Aycin and Benekohal 1998, 16):

$$a_f = -\frac{(v_f)^2}{(2 * d_f)} \quad (31)$$

This above acceleration equation is used instead of the car-following equation from before. "This collision avoidance equation is intended to modify the car-following algorithm and it is applied when the vehicles are in car-following" (Aycin and Benekohal 1998, 16).

## **2.4 Intelligent Cruise Control Safety Issues**

Evaluations of the effects of ICC on time headway, braking behavior, reaction time, and driver workload have been previously described. There are, however, additional in vehicle safety issues that need to be considered. This section describes two state-of-the-art ICC safety issues: seat belt lockouts and foot placement sensors.

### *2.4.1 Seat-Belt Usage*

Deceleration and non-belted drivers may be an issue of consideration. “The potential appears to exist for the development of ICC systems that have sufficiently high levels of deceleration authority to allow an un-belted driver or passenger to ‘submarine’ under the dashboard, or into the rear of the front seat” (Sayer 1996, 14). Due to this potential movement of driver and passengers it is suggested that seatbelt lockouts be considered for standardization (Sayer 1996, 14). An additional concern is that the position of the driver’s legs may not be such to provide bracing on the floor while the ICC is turned on (Sayer 1996, 14). This is addressed in the next section.

### *2.4.2 Foot Placement*

As indicated in the previous section, the placement of feet away from the pedals may mean poor bracing when deceleration occurs with the use of ICC. It is frequently found that drivers do position their feet away from the pedals while using either conventional or intelligent cruise control (Sayer 1996, 14). This results in a longer reaction time where the use of either the accelerator or brake pedal is required (Sayer 1996, 14). It is further suggested that foot placement sensors be used so that the ICC control system could possibly increase vehicle headway when the driver’s feet are away from the pedals (Sayer 1996, 14).

## 2.5 Summary

ICC controls both vehicle speed and headway. Intelligent Cruise Control systems use speed, steering angle, throttle opening, and target vehicle sensors. A camera is used for lane detection purposes. A controller determines the target vehicle, desired speed and initiates action.

Pipes (May 1990) determined the minimum safe distance headway based on the speed of the follower vehicle and the length of the lead vehicle. For each 10 mile per hour increase in follower speed the minimum safe distance headway increases by the length of the lead vehicle. Forbes (May 1990), however, used the reaction time and speed of the lead vehicle. Since May (1990) indicates good agreement between both models and field test results, there is no definite advantage of one over the other.

The equations given for the driver model, General Motor's model and linear acceleration model are presented on the basis of desired acceleration. Each incorporates relative velocity and a form of distance headway. Both the driver model and the linear acceleration model are based on actual headway and desired headway whereas the fifth level General Motor's model uses the velocity of the follower with the actual distance headway. The General Motor's model is more generalized compared to the driver model due to the inclusion of exponents in the sensitivity term. The linear acceleration model bases the next time frame's acceleration on the previous interval's acceleration and acceleration rate (which includes the reaction time). The five driving zones model also considers range and range rate but with much more attention given to driver perception than the linear model. As Fancher and Bareket (1998) indicate, the command velocity equation (zone 4) involving both range and range rate has been used in a prototype Autonomous Cruise Control system. Neither of the other two models specifically incorporate reaction time into the equation but rather indicate that the acceleration determined does not occur until the reaction time has passed.

Intelligent Cruise Control may effect transportation system safety through braking, acceleration, reaction time, headway, driver workload, and velocity. Limitations on the amount of braking provided by the ICC system may depend on seatbelt lockout issues due to the potential movement of passengers and driver with automatic braking. Through platoon simulation it is suggested that ICC may reduce frequencies of hard acceleration and deceleration. Since drivers position their feet away from pedals while using cruise control reaction times are considered to increase when either the accelerator or brake pedal is required. The Swedish Road and Transport Research Institute VTI Simulator Study, however, found no statistical difference between ACC and manual operations with respect to reaction time. Various studies have addressed the effects of ICC on headway. It has been suggested that headway is more consistent with the use of ICC and that desired headway is reached faster (in platoon) with the aid of ICC. In addition, the work of Chira-Chavala and Yoo (1993) with respect to accident analysis shows that ICC may have an impact on accident situations where the cause of the accident is close following. Several studies have also tried to show the effects of ICC on driver workload. The Mitsubishi tests found that driver operations decreased with the use of ICC compared to CCC use. The baseline system test performed by University of Michigan Transportation Research Institute shows a decrease in driver workload found by driver survey. The Swedish Road and Transport Research Institute Simulator Study showed no statistical difference between ACC and manual operations with respect to workload. The University of Michigan Transportation Research Institute baseline system test showed no statistical difference in the three driving modes (manual, CCC, ACC) to velocity. What is indicated is that ACC is more responsive to relative velocity than the driver is.