Adaptive Cruise Control, System Optimisation and Development for Motor Vehicles

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Conventional cruise control systems fulfil the function of automatic speed control. A desired speed is selected by the driver, and a control system operates on the throttle to maintain this desired speed. When traffic density is moderate or high, the driver is faced with having to adjust the set speed regularly in order to maintain a comfortable distance from preceding vehicles and will frequently have to brake, disengaging the cruise control. Thus conventional cruise control can become a source of irritation when used in moderate or heavy traffic. If a distance sensor is added to a conventional cruise control system, then it is possible to add distance keeping to the basic speed control function. This forms the basis for adaptive cruise control, which can be further improved if a limited authority braking system is incorporated. Use can then be made of both throttle and brake actuators to control the distance and relative velocities between a vehicle and a preceding target vehicle.

KEY WORDS

1. Road vehicles. 2. Automation. 3. Design.

1. INTRODUCTION. Speed or Cruise Control systems for passenger cars have been available for many years and are often a standard feature on vehicles sold in North America. Their popularity is greater in North America than compared to say Europe because there is more opportunity to use the feature when speeds can be sustained for long periods of time without the need for adjustment. Conditions of low traffic density, similar cruise speeds and straight roads make Cruise Control a useful feature. However, the contrary conditions more prevalent in Europe[1,2,3] mean that maintaining a constant speed for any time is less likely.

Adaptive Cruise Control (ACC) builds on the traditional Cruise Control feature by enabling the vehicle to reduce its speed automatically from the speed set by the driver when traffic is sensed ahead and then allowing the vehicle automatically to resume the set speed when the path ahead is clear. The system will not apply full emergency braking as ACC is not intended to be a collision avoidance system. ACC is intended to be primarily a comfort and convenience feature[4] designed to cope with relative velocities up to an approximate maximum of 40 miles per hour. Restriction of the maximum braking level to around 0·2 g ensures that there will be situations where the driver has to intervene while still providing a high level of convenience. ACC is being introduced in Europe this year and is likely to become commonplace in the years ahead.

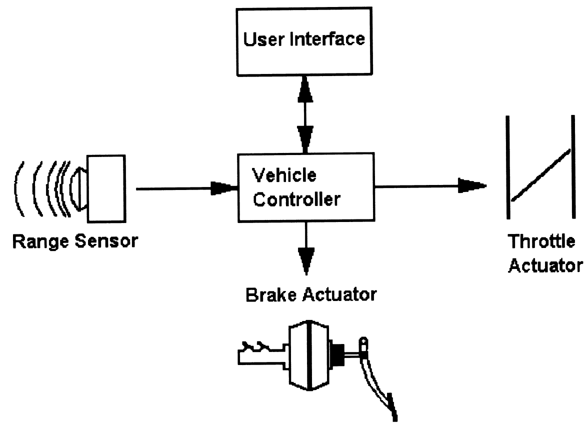

Figure 1. ACC system block diagram.

2. SYSTEM COMPONENTS

2.1. *Range Sensor*. Optical and Laser based sensors can be used as the range sensing, but Radar demonstrates advantages in the following areas:

- Sensor range of 150 m is achievable,
- Sensor can be packaged behind plastic surfaces,
- Performance is less sensitive to weather conditions.

Spectrum allocation dictates the maximum basic radio frequency operating parameters of proposed radars. Collaboration between the US and European committees discussing the technical parameters is taking place in an attempt to provide a common overall standard. Discussion is currently centred around an exclusive 1 GHz wide portion of the radio spectrum from 76–77 GHz. First generation radar sensors being used today were developed from millimetric-wave missile seekers, but the cost constraints of the automotive industry have forced designers to find novel low cost/high volume solutions. The optimum sensor is envisaged to be a single unit comprising the millimetric-wave front end, with integral signal processing and data processing, and a serial link providing data to the Engine Management System, Braking System and Driver Interface.

Sensor size and placement is a critical issue for automotive manufacturers. The sensor will be required to be placed in the frontal area of the vehicle with an unobstructed view of the road ahead. Issues that must be considered include:

- Styling effect,
- Engine cooling effect,
- Susceptibility of the sensor to damage, and crash worthiness,
- Sensor performance,
- Manufacturing and service accessibility.

The frontal area is dominated by the aperture size of the antenna, which is in turn related to the radar beam-width and radar frequency. The beam-width of the radar is related to the antenna aperture size, to a first approximation, by the expression:

$$\phi = \frac{\lambda}{d} \text{radians,}$$

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where ϕ is the radar beam-width in radians, λ is the radar wavelength and d is the size of the aperture in metres. So, for example, for a radar beam to cover 3° in azimuth using a 77 GHz radar (wavelength 3·9 mm) the aperture is required to be about 80 mm wide. This provides encouragement to increase the radar operating frequency still higher, to possibly 152 GHz and maybe beyond, in future, to reduce the sensor size.

The incorporation of radar in a car also requires the use of high speed, low cost, high integrity signal processing as well as low cost high performance vehicle dynamics measurement sensors. Increasingly sensor manufacturers are considering ASICs to reduce the signal processing load and consequently the size, cost, weight of the sensors. However, the ever increasing level of performance and decreasing cost of signal processing will probably ensure that the rf (radio frequency) portion of the sensor generally has the greater cost. The rf portion of the sensor is an area that has potential for cost reduction as designs mature. Currently the Gunn diode is the favoured choice for transmitter power generation and will probably be used initially; however, MMICs at 77 GHz are feasible and in future will be used to provide transmit and receive functions in a single low cost component.

2.2. *Braking System.* The requirement for the braking system is the ability to apply the brakes under the vehicle controller safely and smoothly. Maximum braking levels in the range 0·15 to 0·35 m/s^2 are envisaged for ACC operation. Higher levels of braking would mean that the driver would rarely have to intervene. Since the ACC system is primarily designed for comfort, the maximum automatic braking force is chosen to be at a level where the driver is not relieved of the responsibility for braking and is ready to react in an emergency situation.

2.3. *Throttle System.* The throttle actuation system can be similar to that used in standard cruise control and is typically a stepper motor based system, or in the case of a drive by wire system an electric servo-control system.

2.4. *Driver Information.* Information given to the driver includes the following:

- Vehicle has a target vehicle to follow,
- Set speed,
- Follow distance/headway,
- System at maximum braking level,
- System cancelled/overridden.

3. ACC DYNAMIC CONTROL. The controller has to be capable of operating under two modes of control. Firstly maintaining a desired speed, as for a conventional cruise controller, and secondly the ability to control the vehicle under headway control maintaining the desired headway and target vehicle speed. These two controllers are widely different in their aims; a speed controller, for example, has a quantifiable measurement that is displayed to the driver, which can be checked periodically. The headway controller does not possess such a quantity, the desired distance between two vehicles being a function of the speed of the target vehicle. The restrictions on the headway controller are therefore less tangible and as a consequence are more dependent upon the users' determination as to the comfort and the safety of the overall system. Headway control raises the issue of whether the system matches the driver expectations with regard to braking and headway control. This has been investigated using a combination of simulation and on road trials.[3]

3.1. *Vehicle Modelling*. The primary model used for simulation studies is based upon the consideration of two masses moving in the same direction, one representing the target vehicle the other the following vehicle. If a target vehicle and a following vehicle are moving with speeds $v_2(t)$ and $v_1(t)$ respectively, then the distance between them is a distance x(t). The following vehicle has an acceleration force Ft applied to its mass M_v to produce an acceleration. This vehicle will also have retardation forces Fd acting upon it, which will attempt to reduce the body to rest. A model can then be developed using these ideas that describes the ACC longitudinal control. A schematic diagram of this model is given in Figure 2.

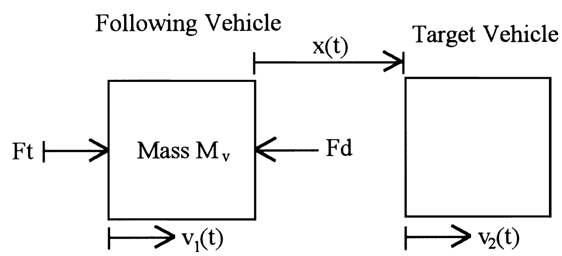

Figure 2. Dynamic system block diagram.

The dynamics of the model can be developed from two equations that describe the rate of change of the distance x(t):

$$\frac{dx(t)}{dt} = v_2(t) - v_1(t),$$

and the acceleration of the following vehicle:

$$M_v \frac{dv_1(t)}{dt} = Ft - Fd.$$

Using these simple laws of motion, a model can be developed that makes use of the state-space model structure. Where the states of the system are taken to be the distance between the following and the tracking vehicle, x(t), and the following vehicle's speed $v_1(t)$. These two states are chosen since they are the parameters that have to be controlled either under headway control or when the vehicle is in speed control.

3.2. *Control Issues*. The controller can make use of the throttle to accelerate the vehicle and the brakes to decelerate the vehicle; however, for the majority of the time under normal driver control, the acceleration and deceleration of the vehicle is maintained by use of the throttle alone. The controller can decelerate the vehicle by making use of either the throttle or the brakes, engine braking being used for the small decelerations and conventional braking used for the larger decelerations. The controller developed makes use of a state-variable feedback controller, which allows the desired response of the system to be obtained from the position of the system pole locations. The point at which the changeover is made from speed control to headway control, under automatic target acquisition, should be robust to the response of the target vehicles. For example, if the relative velocity is high then the distance at which the transition is made should be higher than if the relative velocity of the target vehicle is lower. When the transition is made from speed to headway control, the controller must provide a deceleration or at least a similar level of acceleration to that achieved under speed control.

3.3. *Mitigation of ACC Limitations*. ACC is not able to anticipate the appropriate action in all scenarios. For the most part, human beings have better senses and can use their experience to take the appropriate action far more effectively than if left to ACC. The following are some of the instances where ACC is limited in effectiveness and the methods employed to improve the system.

3.3.1. *Loss of Target Around Bends*. Once the target is judged to be no longer in-path the ACC vehicle will resume the set speed previously selected by the driver (Figure 3). The system has some capability to predict a curving path based on the

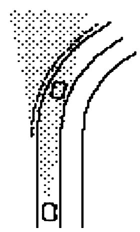

Figure 3. Loss of target vehicle around a bend.

ACC vehicle's yaw rate, but this is limited by the field of view of the sensor and the fact that the ACC vehicle dynamics will lag those of the target vehicle. Current remedies include inhibiting the resume acceleration with respect to yaw but ultimately sensing of the road scenario ahead is desirable.

3.3.2. *Vehicle Cut-in*. Humans are good at evaluating what action to take in different scenarios (Figure 4). To emulate the appropriate action during a cut-in

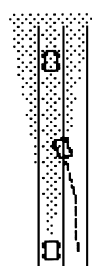

Figure 4. Vehicle cut-in.

manoeuvre a proportional plus derivative control loop is employed to adjust the speed control system by using two separate control laws. The first (labelled as station-keeping) is intended to control the host vehicle capture of proper spacing behind a slower moving target vehicle as the host vehicle catches up to the leading vehicle. The second (labelled as cut-in) provides a reduced dependence upon quick brake response for the cases where an over-taking vehicle suddenly cuts in front of the ACC host vehicle.

In the *fuzzy logic* computation, the speed adjustment request from the station-keeping computation and the cut-in computation are compared in magnitude. The

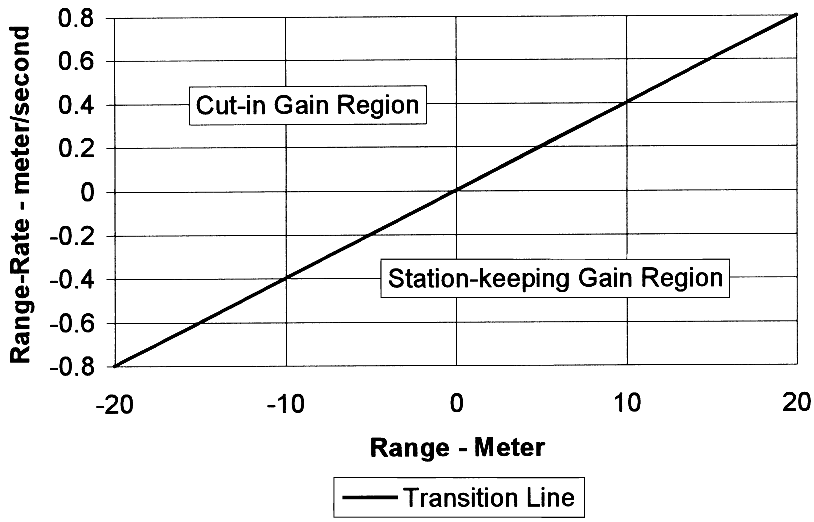

Figure 5. Control phase plane chart.

largest of these requested changes is used to provide commands for throttle and braking actions. For the cut-in manoeuvre, the normal response will require engine retard and some brake action. For this regime, the tuning of gains will make the control system defend its headway more aggressively when the closing rates are small. The following phase-plane chart (Figure 5) shows the transition from the station-keeping to the cut-in gain setting for the calibrations used on the system.

REFERENCES

[1] Becker, S. et al. Summary of experience with autonomous intelligent cruise control (AICC). Part 2. Results and conclusions. *Proceedings of the First World Congress on Applications of Transport Telematics and Intelligent Vehicle–Highway Systems* (*Paris*), (Ed. Ertico), pp. 1836–1843.

[2] Hounsell, N. B., Barnard, S. R., McDonald, M. and Owens, D. (1992). *An investigation of flow breakdown and merge capacity on motorways*. TRL Contractor Report 338.

[3] Analysis of vehicle headway on UK motorways. (1993). *Report for Jaguar Cars Limited by TRL*, August 1993.

[4] Chira-Chavala,T. and Yoo, S. M. (1994). Potential safety benefits of intelligent cruise control systems. *Accident Analysis and Prevention*, **26,** pp. 135–146.