Flow Benefits of Autonomous Intelligent Cruise Control in Mixed Manual and Automated Traffic

B. S. Y. RAO AND P. VARAIYA

Autonomous intelligent cruise control (AICC) is a technology for driver convenience, increased safety, and smoother traffic flow. AICC also has been proposed for increasing traffic flow by allowing shorter intervehicle headways. Because an AICC-equipped vehicle operates using only information available from its own sensors, there is no requirement for communication and cooperation between vehicles. This format allows gradual market penetration of AICC systems, which makes the technology attractive from a systems implementation standpoint. The potential flow increases when only a proportion of vehicles on a highway are equipped with AICC were examined, and theoretical upper limits on flows as a function of pertinent variables were derived. Because of the limitations of the theoretical models, a simulator was used that models interactions between vehicles to give detailed information on achievable capacity and traffic stream stability. Results showed that AICC can lead to potentially large gains in capacity only if certain highly unrealistic assumptions hold. In reality, the capacity gains from AICC are likely to be small.

There is considerable interest in autonomous intelligent cruise control (AICC) technology within the advanced vehicle control system (AVCS) research community. For the purposes of this paper AICC technology is defined as a means of implementing the longitudinal control of a vehicle on the basis of the measurement of its speed and distance relative to the vehicle in front of it, together with measurements of its own state (*1–3*). Because these measurements can be obtained from sensors placed on the vehicle, the control law requires no cooperation from other vehicles—hence the term "autonomous." Consequently, AICC-equipped vehicles, in principle, can operate together with manually controlled vehicles. AICC technology thus provides an intermediate step toward the automated highway system (AHS) in which a vehicle's controller relies on information received from other vehicles.

Proponents of AICC make two sets of claims. The first set of claims concerns how well a single platoon of AICC-equipped vehicles follows a lead vehicle that undergoes a specified speed profile. The claims are about the stability of the platoon, the absence of the "slinky" effect, and the magnitudes of acceleration and deceleration induced by the control law. We shall not examine these claims here.

We examine here the second set of claims that concerns the increases in the capacity of a highway used by vehicles some or all of which are AICC equipped. The analysis supporting these claims is based on steady-state flow relations derived from the investigation of a single platoon. The validity of such an analysis rests, as we shall show, on a number of assumptions about the behavior of the lead vehicle of a platoon of AICC-equipped vehicles and the way in which (manually driven) vehicles merge into a lane containing platoons. We shall make these assumptions explicit.

We derive a theoretical upper bound on the capacity gain using AICC for various degrees of market penetration. We then describe results of a simulation in which the behavior of vehicles is modeled at a detailed level, showing how it has been applied to give information on achievable capacities and stream stability.

We conclude that AICC can offer modest improvements to lane capacity at low market penetration levels and probably has a beneficial, if slight, effect on stream stability. At higher levels of implementation, greater increases in capacity become harder to achieve because of problems of stream instability and limits on the rates at which vehicles can be fed into highways.

INITIAL MODEL FOR PREDICTING FLOW BENEFITS

We begin by modeling the process by which platoons are formed using AICC and attempt to derive theoretical upper bounds for capacity improvements for a range of degrees of implementation. "Platoons" in this case refers to groups of vehicles following each other at relatively close headways under AICC.

The basis formula to calculate flow in vehicles per hour is

$$\text{Flow} = \frac{3600 v \overline{N}}{\overline{N}(l + d) - d + \overline{\Delta}} \quad (1)$$

where

v = vehicle speed (m/sec);
l = length of a car (m);
d = spacing between cars in a platoon (m);
$\overline{\Delta}$ = average spacing between platoons (m); and
$\overline{N}$ = average size of a platoon:

$$\overline{N} = \sum_{1}^{\infty} Np(N)\, dN \quad (2)$$

California PATH, Institute of Transportation Studies, University of California, Berkeley, Calif. 94720.

In an "adaptive" platooning scheme such as this, an increase in demand gives rise to a natural increase in platoon sizes and a decrease in interplatoon spacings. The relationship between $\overline{N}$ and $\overline{\Delta}$ is

$$\overline{\Delta} = \overline{N}(\overline{\Delta}_{man} - d) + d \tag{3}$$

The value $\overline{\Delta}_{man}$ is the average headway of manually controlled vehicles (before platooning starts).

It is clear that to derive the flow we must derive the platoon size distribution, $p(N)$.

In the ensuing analysis we denote any term pertaining to the vehicle in question with a subscript k and any term pertaining to the vehicle behind it with the subscript $k - 1$. The following terms are defined:

- $p(\text{man})$ = probability that a car is manually driven;
- $p(\text{aicc}) = 1 - p(\text{man})$ = probability that a car is AICC equipped;
- $p(\text{leader})$ = probability that a car is a leader of a platoon;
- $p(\text{follower}) = 1 - p(\text{leader})$ = probability that a car is in a platoon but not the leader;
- Δ_k = headway of Vehicle k before platooning begins;
- Δ_{max} = maximum distance a car can detect another car;
- $p(\Delta_k > \Delta_{max})$ = probability that Car k cannot detect the car ahead;
- $p(\Delta_k < \Delta_{max})$ = probability that Car k can detect the car ahead; and
- $p(\Delta)$ = probability distribution of vehicle headways before platooning begins.

SCENARIO

The modeled scenario is shown in Figure 1. There is a single manual/AICC lane (the inside lane in Figure 1), an adjacent "transition" lane, and several entrance ramps that allow vehicles to enter at a regular metered interval rate. We assume that a certain fraction of all vehicles have AICC capability. Vehicles are initially traveling at some flow ϕ along a single-lane highway under fully manual control. We assume that the flow in the manual part of the inside lane is restricted to 1,800 vehicles/hr, with headways drawn randomly from a distribution that models the way drivers behave on highways (*4*) (see Figure 2). At some fixed point along this highway those vehicles equipped with AICC are allowed to activate their systems. We assume that all vehicles equipped with AICC that can detect the vehicle in front of them in the manual section form a platoon with those vehicles once they have entered the automated section and that there is no limit on potential platoon size.

We assume that some vehicles from the on-ramps are attempting to enter the inside lane; because we are attempting to find an upper bound on flow in that lane, we assume that only AICC-equipped vehicles attempt to enter the inside lane from the transition lane.

We wish to derive the platoon size distributions for various input flows and for increasing proportions of vehicles equipped with AICC. This will allow us to calculate the flow on the highway once all vehicles have settled to steady state (i.e., all platoons have been formed).

Analysis

We begin by analyzing the formation of platoons in the inside lane as vehicles enter the AICC region (see Figure 3). To form a platoon of any size, the first requirement is for a leader. A leader is either a manual vehicle or an AICC vehicle that cannot detect the vehicle in front of it. Therefore

$$p_k(\text{leader}) = p_k(\text{man}) + p_k(\text{aicc} \wedge \Delta > \Delta_{max}) \tag{4}$$

For a platoon of size N there must be a leader (k) followed by a line of $N - 1$ AICC vehicles that are close enough to each other before platooning starts that they can each detect the preceding vehicle, followed finally by either a manual vehicle or an AICC vehicle that is too far to detect vehicle $k - (N - 1)$; in other words, another leader (see Figure 3). Therefore the probability of generating a platoon of size N from

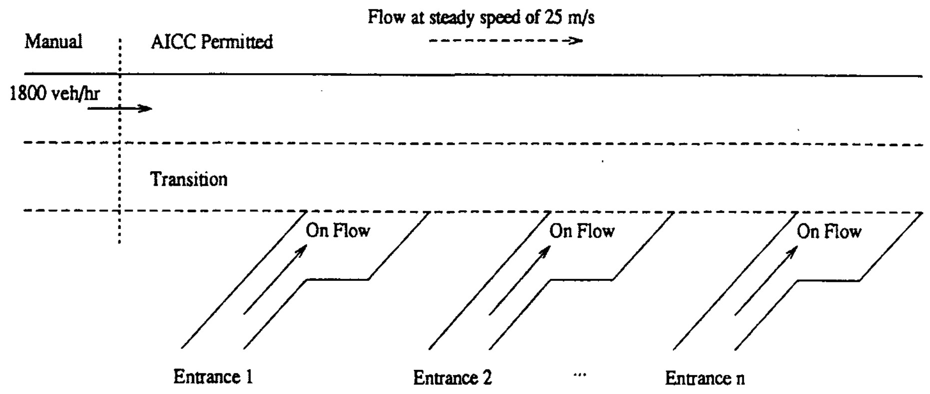

FIGURE 1 Diagram of the highway section modeled.

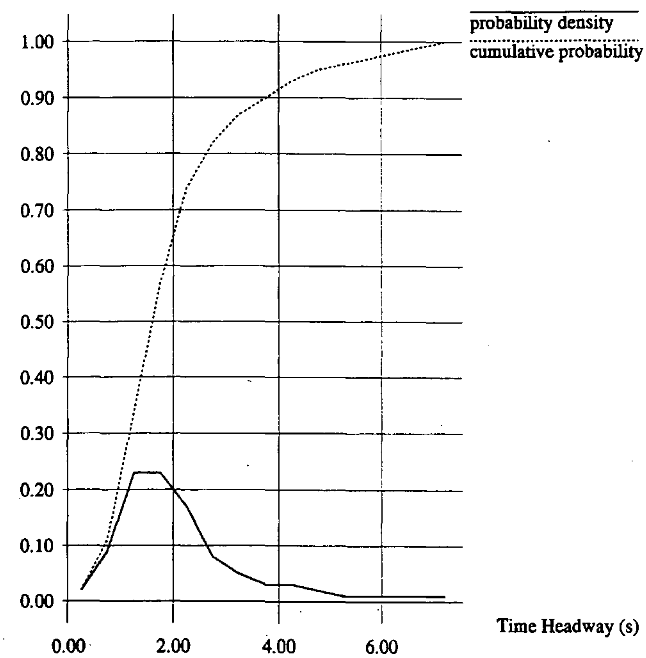

FIGURE 2 Maximum flow rate found on highways currently is about 1,800 vehicles per hour per lane. Drivers under such conditions exhibit a range of time headways. If a vehicle is traveling at 25 m/sec and can detect up to 60 m, it is clear that $p(\Delta) < \Delta_{max}) \approx 0.7$. This distribution is after May (4).

vehicle k is

$$p_k(N|k) = p_k(\text{leader}) \prod_{n=1}^{N} [p_{k-(n-1)} (\text{aicc} \wedge \Delta < \Delta_{max})]\, p_{k-N}(\text{leader}) \quad (5)$$

If we now assume that $p_k(\text{man})$ [and $p_k(\text{aicc}) = 1 - p_k(\text{man})$] is independent of $p_k(\Delta)$ and that $p_k(\text{man})$ and $p_k(\Delta)$ are independent of k, then we can rewrite as follows (dropping redundant k's):

$$p(\text{leader}) = p(\text{man}) + p(\text{aicc})p(\Delta > \Delta_{max})$$

$$p_k(N|k) = p(\text{leader})^2\, [p(\text{aicc})p(\Delta < \Delta_{max})]^{N-1}$$

Because in a platoon of size N we could equally have started with any vehicle within that group of cars, we can say that our choice of vehicle k is a 1 in N chance for that particular group of cars. Therefore

$$p(N) = p_k(N|k)p(k) = p_k(N|k)(1/N)$$

$$p(N) = Np(\text{leader})^2\, [p(\text{aicc})p(\Delta < \Delta_{max})]^{N-1} \quad (6)$$

This is a beta distribution, and it is clear that $p(N)$ is dependent on $p(\text{aicc})$, $p(\Delta)$, and Δ_{max}.

We then assume that after each on-ramp there are a certain number of AICC vehicles in the transition lane that wish to enter the inside lane. We model this situation as shown in Figure 4. Given any platoon in the inside lane, we assume that all AICC-equipped vehicles in the transition lane that are within a "catchment" region will eventually join that platoon. The size of the catchment region for a platoon of size N is $L(N)$ and is defined by the method by which vehicles join platoons. Because there is insufficient intervehicle spacing in a platoon for vehicles to merge into a platoon safely and it may not be possible for vehicles in the adjacent lanes to accelerate to join the front of a platoon, we assume that vehicles have to join the rear of platoons. Therefore, we can postulate a requirement for safe maneuvering distance δ in front of a platoon within which vehicles attempting to join the platoon in front cannot encroach. This defines the size of Catchment Region 3 to be

$$L(N) = \delta + N(l + d) - d + (\Delta - \delta)$$
$$= N(l + d) - d + \Delta$$

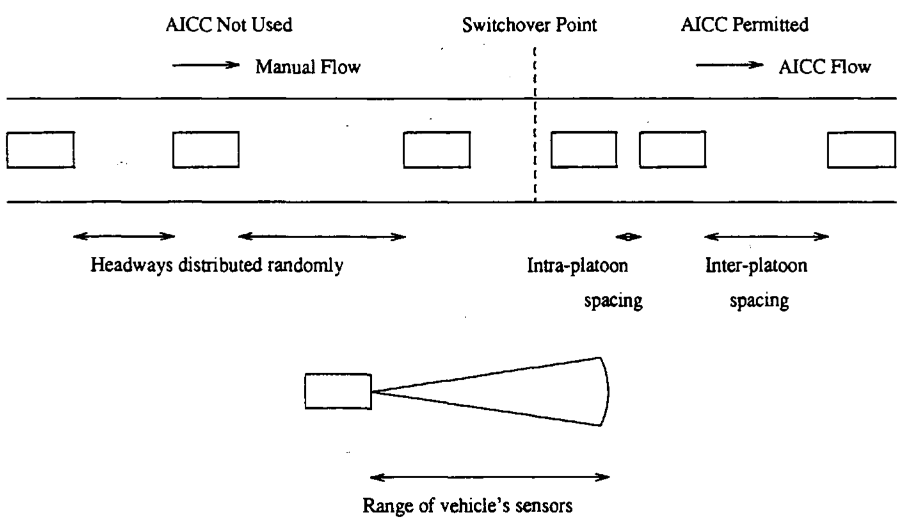

FIGURE 3 How vehicles platoon initially. It is assumed that manually controlled, randomly distributed vehicles enter a section of highway where AICC can be used. Platoons are formed in the AICC section as vehicles detect their predecessors. The lower figure shows the range of detection of a vehicle using on-board sensors.

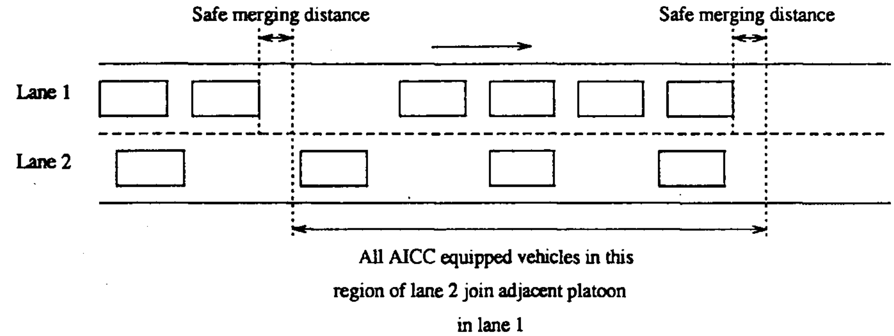

FIGURE 4 The scenario modeled. Vehicles in the transition lane (Lane 2) attempt to enter the AICC lane (Lane 1) and form platoons using AICC. It is assumed that all AICC vehicles within a platoon's catchment region will eventually join that platoon.

Given a flow ϕ_t of cars in the transition lane, regularly spaced from ramp metering, we say that the number of vehicles in the transition lane within the catchment area of a platoon is q:

$$q = \frac{L(N)\phi_t}{3{,}600\upsilon}$$

We say that all AICC-equipped vehicles in a platoon's catchment area eventually will join that platoon so that a new probability distribution for platoon size $p'(N)$ can be derived from the old one $p(N)$:

$$p'(N) = \sum_{n=1}^{N} [\gamma p(n) p(\text{aicc})^{N-n} p(\text{man})^{q-(N-n)}]$$

$$\gamma = \begin{cases} 0 & q - (N - n) < 0 \\ \dfrac{q!}{[q - (N - n)]!(N - n)!} & \text{otherwise} \end{cases}$$

The new distribution is calculated as the probability of ending up with a new platoon of size N starting with a platoon of size n and adding $N - n$ vehicles from an available number q, given a particular p(aicc).

Caveats

After a number of AICC-equipped vehicles have entered the inside lane, the proportion of AICC-equipped vehicles in the inside lane will not be the same as it was in the manual part of the lane; however, since we are attempting to find the maximum flow in a lane we only investigated this case. By allowing vehicles to enter through merging we can assume that any vehicle that has the capability to join a platoon will eventually do so.

We assume several discrete entrance points and that vehicles from these entrances join the inside lane as soon as possible. In reality it may be that drivers enter the highway and that only after some time do they try to enter the inside lane. Relaxation of this assumption would not alter the capacity of the inside lane but may allow a higher flow on the transition lane by spreading out the flow of vehicles wanting to enter the inside lane.

Another drawback of our model is that we do not allow vehicles to enter the inside lane unless it is to join an existing platoon. Formation of new platoons in the inside lane would expedite the process of moving vehicles into that lane.

Results

We investigated a scenario in which a flow of 1,800 vehicles/hr was on the inside lane in the manual section. We set p(aicc) to the proportion of AICC-equipped vehicles initially on the highway. We evaluated the maximum flow that could result from a given distribution of platoon sizes and set $\overline{\Delta} = \overline{\Delta}_{man}$. Each platoon leader behaved as though driving in a manual lane and thus gave rise to the headway distribution found on such a highway lane.

Choice of Δ_{max} can be anywhere between 20 m if the vehicles are going around a bend in the rain at night to 150 m (*2*) if the vehicles are on a straight flat stretch of road in the daytime. Since we are attempting to derive an upper bound, we assume that Δ_{max} is maximized.

There are six entrances, each at a spacing of 1 km with the first at 1 km after the AICC section starts. On-ramp flows are such that AICC vehicle flows from the transition lane to the inside lane constitute a rate of 720 vehicles/hr. We calculated the platoon size distribution after each entrance, assuming that all the vehicles that wanted to enter the inside lane had done so. From these distributions we calculated the maximum possible flow.

Manual flow was calculated by the formula

$$\text{Flow} = \frac{3{,}600\upsilon}{l + \Delta_{man}}$$

and was used as a reference for calculating percentage capacity gains. We take the speed $\upsilon = 25$ m/sec, the length of a car $l = 5$ m, the average headway $\overline{\Delta}_{man} = 45$ m, and the intraplatoon spacing $d = 8$ m (*1*). Despite a previous analysis (*1*), we believe this to be an extremely optimistic value; in reality the intervehicle spacing may have to be higher to allow vehicles to stop without colliding in the case of emergency braking (*5*), but we use this value because we are interested in an upper bound. Because in this model it is not $p(\Delta)$ but $p(\Delta < \Delta_{max})$ that is of importance, we obtain results for a range of values for $p(\Delta < \Delta_{max})$. Note that for the assumptions made, the capacity of the inside lane is at maximum (using Equation 1), (3,600 × 25)/(8 + 5) = 6,900 vehicles/hr. Results are shown in Figure 5.

Obviously a greater number of AICC vehicles at the start allows the flow to build faster through formation of more and larger platoons, but predicted growth of all flows slows down as capacity is approached. This model shows that capacity can be attained but may take a long time to achieve.

DETAILED KINEMATIC SIMULATION TO ANALYZE AICC

The above analyses allowed us to gain some knowledge of likely platoon size distribution and potential flow benefits using AICC; however, because they are fundamentally steady-state analyses they can afford no information on stream stability, likely access rates, or access times for vehicles in such systems. Since merge junctions are likely to be the principal sources of delay and capacity limitation of an (even partially) automated system, it is necessary to progress beyond steady-state analysis and examine transient behavior (*6*).

To study these phenomena we use a modified version of SmartPath (Eskafi) (*7*), a detailed, multiprocess kinematic simulator used to aid design of coordinated platooning strategies. The simulator has been modified to allow accurate representation of the behavior of AICC-controlled and manually driven vehicles (Figure 6). The control policies proposed previously (*1*) have been used to model the dynamics of AICC vehicles.

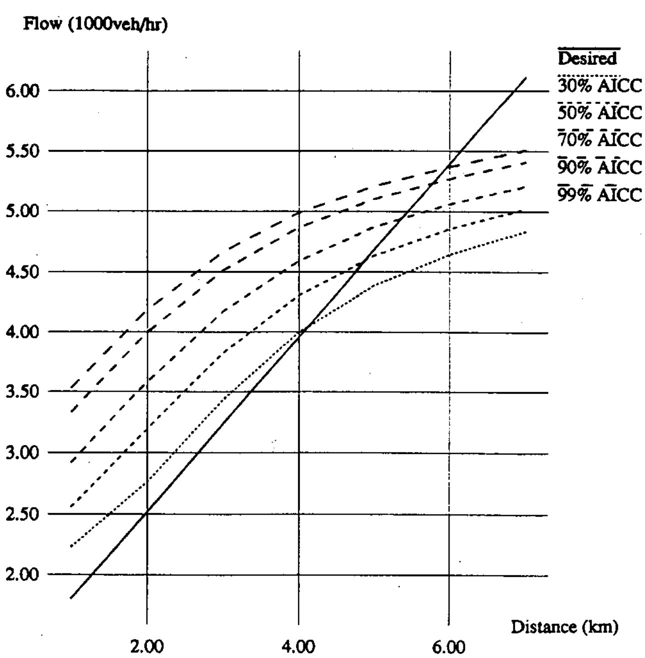

FIGURE 5 Maximum possible flows on the AICC lane given $p(\Delta < \Delta_{max})$ = 0.7 and different initial proportions of AICC vehicles. As the lane approaches theoretical maximum capacity, the obtained maximum flows begin to lag behind demand as it becomes increasingly hard to find the space to fit in more vehicles.

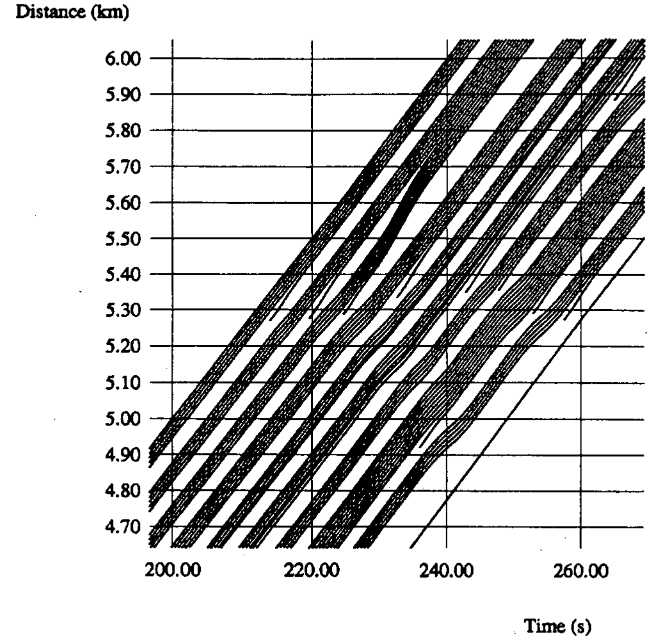

FIGURE 6 Detail of SmartPath output for inside lane showing how vehicles entering the lane join the rear of existing platoons. Opportunistic merging of two platoons is shown.

Scenario

We used the highway configuration shown in Figure 1 and analyzed above. A randomly distributed stream of vehicles at 1,800 vehicles/hr was on the inside lane, traveling at 25 m/sec under manual control. At a distance of 0 km those vehicles that were equipped with AICC used their systems and began to platoon with each other. For this simulation we say that each vehicle can detect up to 60 m ahead. After some distance d_1 the platoons will be in steady state (they will all be separated by at least 60 m). We place the first on-ramp such that all the traffic in the AICC lane is already at steady state by this point. The subsequent on-ramps are also placed sufficiently far along the highway that all the traffic from the previous on-ramp has entered the AICC lane and that the AICC lane is in steady state (Figure 7).

Vehicles that entered from the on ramps were all AICC equipped and immediately tried to enter the inside lane. If there is a sufficiently large (safe) gap adjacent to a car it will enter the inside lane; otherwise it will decelerate until it is far enough behind a platoon to enter the lane and merge with the platoon.

Off-ramps are not included in this simulation because within SmartPath it is not possible to simulate the AICC method of leaving the AICC lane (just pulling out into the transition lane). SmartPath requires the platoon to break and allow a vehicle more room to leave. However, we can still comment on how the AICC exiting strategy may affect stream stability (see conclusions).

Intraplatoon separation was derived in the manner of Ioannou and Chien (*1*) to be 8 m. Interplatoon safety distance was 50 m, and the maximum platoon size was 30. With these parameters the maximum theoretical flow is about 6,250

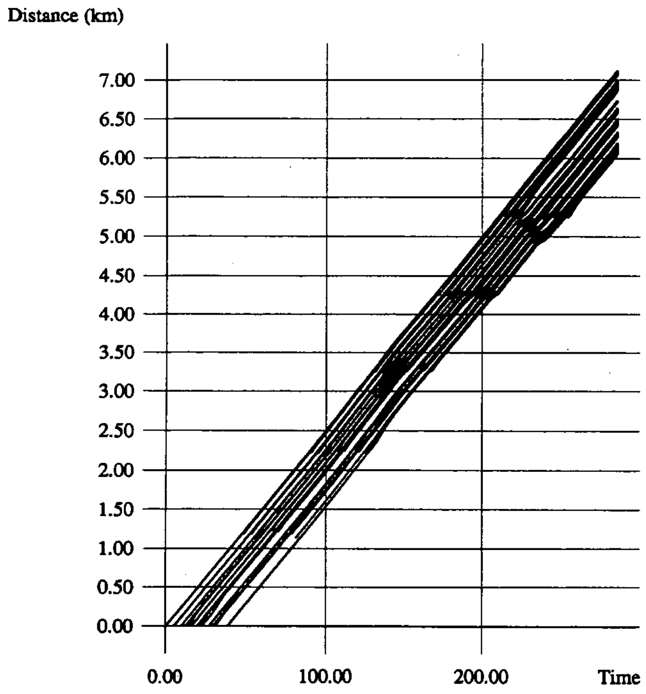

FIGURE 7 Time-distance diagram for the automated lane. Vehicles enter the automated section of the highway at 0 km at a flow of 1,800 vehicles/hr moving at 25 m/sec. There are entrances at 1, 2, 3, 4, and 5 km that release vehicles at the rate of one every 5 sec (720 vehicles/hr). Note how the traffic sample "spreads out" when capacity is exceeded (after 5 km).

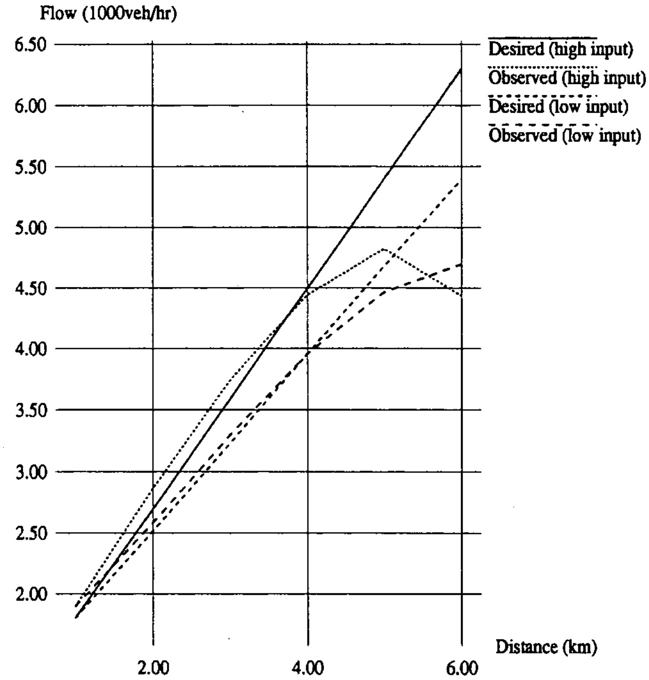

FIGURE 8 After Monte Carlo runs, the average flow on the inside lane at each point along the highway for initial *p*(aicc) = 0.5 is shown. Low on-ramp entrance rates (720 vehicles/hr) track demand better than high rates (900 vehicles/hr).

vehicles/hr. To simulate realistic vehicle dynamics we limit the deceleration of a vehicle during a maneuver to 0.3 *g*.

For different on-ramp flows and at each stage of the highway we attempted to measure the following:

- The maximum attainable flow in the inside lane,
- The maximum sustainable on-ramp flow rate, and
- The effect on stream stability of vehicles entering.

Because all of these are random variables dependent on the initial headways of manual traffic in the inside lane and on exactly how platoons are formed, we obtained our results after Monte Carlo simulations to attempt to average out the effects of the random behavior. The simulation was run 100 times with different starting headways (all drawn from the same distribution), and the cumulative results were analyzed.

Experimentation

To allow results to be obtained within a reasonable time frame we generated a 40-sec section of traffic and monitored the progress of this "sample" as it proceeded along the highway. In the first instance we wished to determine roughly the rate at which vehicles can be input from an on-ramp. Initial experiments showed that when the flow on the AICC lane was high the vehicles in the transition lane had to maneuver significantly to change lanes, resulting in turbulent flow in the transition lane and some vehicles not being able to change lanes at all. It was found that on-ramp flows of 720 vehicles/hr produced the best results, maximizing eventual maximum flow in the inside lane without excessive turbulence (Figure 8). Monte Carlo simulations were therefore conducted using on-ramp flow rates of 720 vehicles/hr.

Results

Figure 9 shows the actual flow rates achieved in the AICC lane. These results are based on averages over the entire Monte Carlo sequence and show that the observed flow rate is lower than might be expected from our model. Initially, when traffic density is low, platooning causes the traffic on the lane to bunch up and thereby increases the measured flow rate over the traffic sample. However, as the density on the AICC lane increases it is found that the length of the traffic sample grows to accommodate new vehicles, thereby effectively reducing the increase in flow. Growth in the flow rate therefore slows down as flow on the AICC lane increases as expected.

Obtaining quantifiable results on stream stability is not easy. From the experience of running these simulations we can make the following broad comments. With regard to the AICC lane, it appears that the flow is stable under conditions of vehicles entering the lane, until lane capacity is approached. Vehicles leaving platoons also may not cause perturbations as long as the sudden change in headway for a vehicle following a vehicle about to exit does not cause it to behave erratically. The real source of flow instability in AICC systems is found in the transition lane. Note also that in these simulations there was no permanent flow on the transition lane—

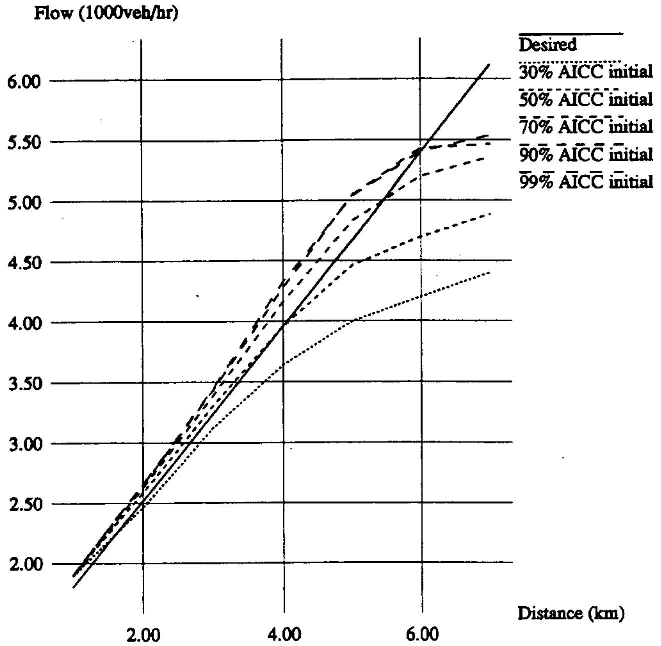

FIGURE 9 Observed flow at regular intervals along the highway using on-ramp flows of 720 vehicles/hr and given various proportions of AICC-equipped vehicles in the initial stage. Demand flow is tracked well until the theoretical capacity of the lane is approached.

only vehicles attempting to join the AICC lanes. Introduction of even a small permanent flow would have severe effects on stream stability, and the maximum on-ramp flow would be curtailed.

Faults in the Simulation Methodology

The above results were obtained using a modified version of SmartPath. This allowed us to investigate AICC quickly, but because the program is designed for another IVHS strategy it implies that not all of the features of AICC can be modeled accurately. The following is a list of areas in which this simulation does not do justice to the concept of AICC:

- We assume that a driver in the transition lane who is adjacent to a platoon and wants to enter the inside lane will take positive action and decelerate to join the back of the platoon. In reality it may be that a speed differential (albeit small) may exist between the two lanes, allowing drivers in the transition lane to simply wait until a safe gap rolls past them and allows them to change lanes. This behavior would reduce the turbulence in the transition lane but may increase the amount of time it takes drivers to enter the inside lane. If, however, the use of AICC is perceived as providing a high degree of comfort, drivers may try to enter a lane where its use is permitted as soon as possible.
- In AICC a vehicle should simply enter the AICC lane if there is a gap; if there is not a gap, a vehicle should slow down until one appears. In SmartPath this logic has been implemented, but a vehicle that is slowing down to join the rear of a platoon is also in communication with it. Because a platoon is able to communicate to only one vehicle at a time, no other vehicle is able to talk to that platoon, which may create cases in which vehicles do not change lanes in a realistic order. However, in the majority of cases this will not occur because the vehicles forced to slow down behind a decelerating vehicle in the transition lane will come across a suitable gap first and merge sooner into the AICC lane on their own.
- One area in which SmartPath is currently deficient is the control law for the lead vehicle of a platoon. (To our knowledge no clear control law for lead vehicles in AICC platoons has been proposed. Merely maintaining a constant speed may not be sufficient to cope with all eventualities.) This law calculates the deceleration a vehicle must apply at each instant simply on the basis of the distance and relative velocity of the vehicle in front so that a collision is always avoided (*8*). The same law is also used for vehicles in the transition lane, and its crude nature leads to situations of traffic stream instability that would not occur with manual drivers. This may have led to a reduction in the maximum on-ramp flow, but at high flows on the AICC lane the problems of large transition delays will remain no matter what control laws are used.
- SmartPath cannot simulate the AICC policy for exiting, which is simply to pull out. However, an exiting policy such as this may not have adverse effects on stream stability in the AICC lane but may cause disruption in the transition lane, especially if there is some permanent flow in that lane.

These drawbacks notwithstanding, some strong conclusions about AICC can still be made from use of the simulator.

Conclusions

AICC seems to provide stable flow and an increased capacity in the automated lane (albeit on the basis of an 8-m value for *d*, which may not be realistic), but it has several drawbacks:

- Building up the flow on the AICC lane takes a long time and perhaps much longer than with coordinated platooning, which can sustain higher on-ramp flows even when flows on the automated lane are very large (see companion paper by Rao et al. in this Record).
- Flow on the transition lane is not very stable when the flow on the AICC lane becomes large.
- The theoretical upper limit on the capacity cannot be attained in any reasonable length of time, and a practical limit on the attainable flow appears to be about 75 percent of the theoretical flow.
- Because the stream in the transition lane is so sensitive to vehicles moving in and out of it, it may prove necessary to ensure that only a very small or even no permanent flow exists on that lane. This implies the need for two lanes with only one in which traffic is actually traveling permanently. Therefore any capacity on the AICC lane must be divided by 2, and if the practical limit is 5,500 vehicles/hr the overall highway flow is 2,700 vehicles/hr per lane, which is only marginally better than highways maintain now. This point is crucially dependent on our model of human vehicle-following behavior, which is admittedly deficient in this simulation. However, given high flow rates it seems reasonable to assume that disturbances in the transition lane are inevitable regardless of the vehicle-following models used.

CONCLUSIONS

Proponents of AICC technology claim significant increases in capacity, but the claim has not been substantiated by convincing analysis in the published literature. We have attempted to provide such an analysis using theoretical models that ignore interaction among vehicles as they attempt to merge and the SmartPath simulation system that does model those interactions.

It is found that the estimates for maximum capacity increases using both approaches agree when the level of penetration of AICC technology is under 40 percent; but at higher levels of penetration the theoretical model overestimates the capacity increase.

The simulator, SmartPath, was then used to study the more difficult problem of stream stability, especially in the transition lane used by AICC-equipped vehicles entering from on-ramps and intending to use the AICC lane. It is found that as the flow entering from the on-ramps begins to reach the values estimated in the previous analysis, it becomes increasingly difficult for vehicles to enter the AICC lane. Taking published values of AICC control strategy, we find that the AICC lane can achieve a flow of 5,500 vehicles/hr—three times the current capacity. However, if this flow is to be achieved, it is not possible simultaneously to have any permanent flow in the transition lane, so that the effective flow per lane is reduced to 2,700 vehicles/hr.

Although these flow rates appear impressive, they are based on an extremely optimistic value for intervehicle spacing in platoons using AICC. This value (8 m) is, in our opinion, too small and is unlikely ever to be implemented for the following reason: If a vehicle is equipped with AICC but has poor brakes or tires, it will be a hazard to any vehicle it follows that is in better condition mechanically (*5*). If a sudden deceleration is required, the vehicle in relatively poor condition will not be able to stop before hitting its predecessor. Apart from the safety issue, this raises the important legislative question of liability.

Because AICC cannot maintain the ultraclose spacings (1 m) required to prevent high relative velocity collisions [as defined previously (*9*)], and the proposed spacings of about 8 m could lead to high relative velocity collisions, we are forced to conclude that spacings comparable with those used by human drivers now will be required for safe operation. This immediately reduces the potential for capacity gain from use of AICC to very low levels, although the potential for increase in driver comfort still exists.

The argument presented here is tentative, and we have made explicit several assumptions that underlie both the theoretical and simulation approaches. We hope the argument will stimulate more careful assessments of the AICC technology.

ACKNOWLEDGMENTS

This work is supported by the California PATH program and California Department of Transportation. The authors would like to thank F. Eskafi, S. Sheikoleslam, S. Shladover, and R. Hall for many useful comments and helpful guidelines.

REFERENCES

1. P. Ioannou and C. C. Chien. *Autonomous Intelligent Cruise Control*. Technical Report 92-05-01. Department of Electrical Engineering—Systems, University of Southern California, May 1992.
2. R. Muller and G. Nocker. Intelligent Cruise Control with Fuzzy Logic. In *IEEE Conference on Intelligent Vehicles*, Detroit, 1992, pp. 173–178.
3. F. Broqua, G. Lerner, V. Mauro, and E. Morello. Cooperative Driving: Basic Concepts and a First Assessment of Intelligent Cruise Control Strategies. *First Drive Proceedings*, 1991, pp. 144–147.
4. A. D. May. *Traffic Flow Fundamentals*. Prentice Hall, 1990.
5. A. Hitchcock. Coefficients of Friction and Automated Freeways. PATH MOU 19 Occasional Paper 1. May 1992.
6. S. Shladover. Operation of Merge Junctions in a Dynamically Entrained Automated Guideway Transit System. *Transportation Research*, Vol. 14A, 1979, pp. 85–112.
7. F. Eskafi and P. Varaiya. *SmartPath: An Automated Highway System Simulator*. Technical Report 92-0708-1. California PATH, 1992.
8. F. Eskafi, D. Khorramabadi, and P. Varaiya. *SmartPath: Automatic Highway System Simulator*. Preprint. Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, June 1992.
9. P. Varaiya and S. Shladover. *Sketch of an IVHS Architecture*. Technical Report UCB-ITS-PRR-91-3. Institute of Transportation Studies, University of California, Berkeley, 1991.

Publication of this paper sponsored by Committee on Intelligent Vehicle Highway Systems.