TECHNICAL FUNCTIONS	AUTOBRAKE	AUTOGAP
DESIRED VEHICLE RESPONSES - INFORMATION NEEDS	DISTANCE, RATE OF CLOSURE OF FORWARD QUADRANT VEHICLE-SIZE OBJECTS IN OWN & ADJACENT LANES. DISCRIMINATION OF NON-THREAT OBJECTS. OWN VELOCITY. REAL-TIME BRAKING CAPABILITY	ESSENTIALLY THE SAME. PROBABLY NEED TO DETECT TURN SIGNALS OF NEAREST VEHICLES.
SENSING AND SENSOR INTERPRETATION	• FIELD-OF-VIEW ROUGHLY FORWARD QUARDRANT. • ESSENTIALLY REAL-TIME PROCESSING. • VERY LOW FALSE ALARM AND FAILURE-TO-ACT RATES. • SPEEDOMETER & LONGITUDINAL ACCELEROMETER.	ESSENTIALLY THE SAME
EXTERNAL INFORMATION, COMMAND INPUTS - COMMUNICATION	NOT REQ'D	PROBABLY NOT REQ'D. IF COMMUNICATION NEEDED, WILL BE TMS-TO-VEHICLE.
VEHICLE CONTROL ACTUATION	ELECTRONIC BRAKING	ELECTRONIC BRAKES AND THROTTLE

Figure 15. Autobrake and Autogap Mechanizations: Functional Description of Technical Elements Required

sensing and sensor interpretation system will also support Autogap. The interpretation system will, of course, require some adaptation.

It is more important for Autogap than Autobrake for the system to be able to continuously track vehicles in adjacent lanes. If not included in Autobrake, it should probably be added.

External Information & Command Inputs - The Need for Communications.

It is our opinion that since a vehicle with ICC is still a driver controlled vehicle, there is no need to transmit traffic commands directly to the automated system, and that the currently used visual signals to the driver are adequate. This would leave ICC as a completely autonomous function, not requiring communication with the infrastructure.

This is an arguable issue.

Vehicle Control Actuation.

The throttle control probably needs to be more sensitively modulated than some cruise control systems currently in use.

It would be sensible to initially design the automated brake system of Autobrake for the level of modulation needed for Autogap (and superior Cruise Control). This will clearly happen if, as we conjecture, Autobrake is only offered for sale when incorporated into Autogap.

System Mechanization.

Figure 16 depicts the mechanization for Intelligent Cruise Control. Comparing it to Figure 12, it can be seen that the changes at the top level shown in the figures are slight. Electronic throttle control has been added, and we now show the driver's control being effected through the electronic system rather than through mechanical linkage.

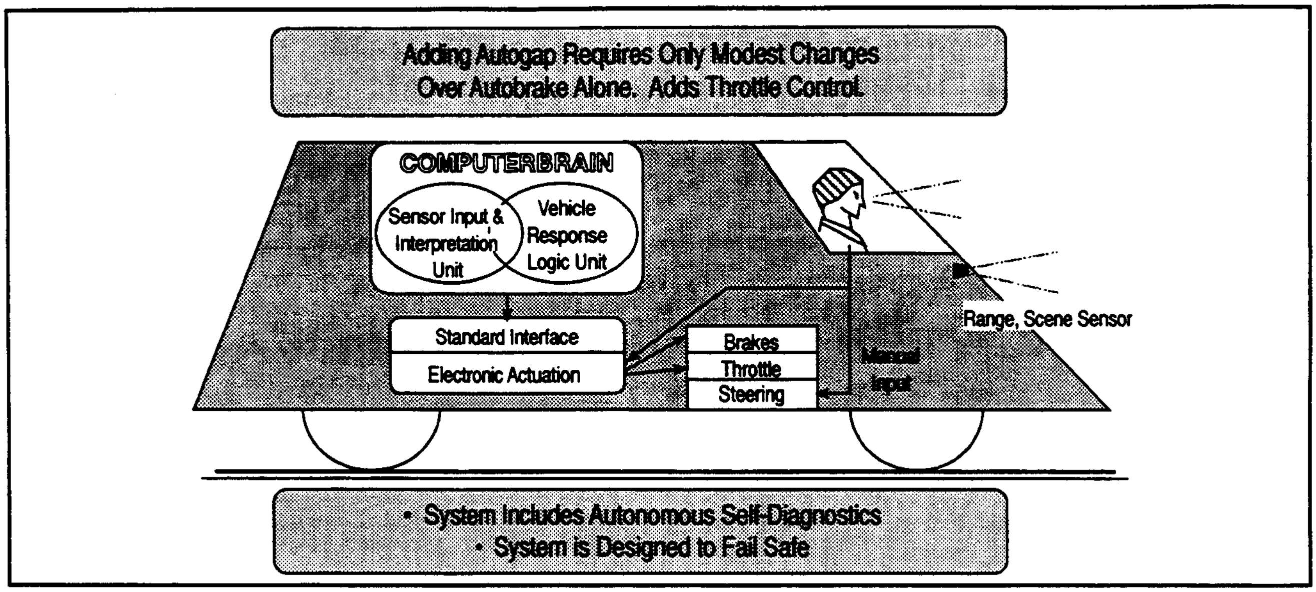

Figure 16. Autobrake and Autogap Mechanization Intelligent Cruise Control

We now turn to a discussion of the potential benefits of the system that might be a motivation to purchase.

POTENTIAL BENEFITS - MOTIVATION TO PURCHASE.

Safety.

While Autobrake offered only "invisible" safety, the combination of Autobrake and Autogap - Intelligent Cruise Control - offers both invisible safety and the obvious safety of not letting Cruise Control, in a moment of inattention, drive one into the vehicle ahead.

Driver Convenience.

The Autogap addition to Cruise Control also offers relief to the driver from the constant attention and drive-train control actions required to maintain one's position in a string of traffic. This speed-up-slow-down is particularly irksome on a crowded freeway operating on the unstable side of the highway capacity curves - an all too frequent event. We conjecture that this aspect of ICC may be the most powerful enticement for purchase of the system.

Capacity Improvement.

While Autogap (because of the Autobrake feature) offers the driver the option of decreasing the following distance down to the safegap corresponding to automatic braking, it's questionable whether many drivers will exercise this option because such close following distances will probably be uncomfortable, at least initially. It is therefore dubious that Autogap will contribute to an appreciable increase in effective lane capacity when first introduced.

But we notice that many drivers seem to not be disturbed by driving very close to the car in front (a number of these frequently follow the author). There is, in fact, an advantage to close following: shortening the gap makes it more difficult for other cars to cut in front of one. This is motivation for many to drive closer than they would otherwise chose. It may be that in time more and more drivers will opt for closer following distances, particularly as the freeway becomes more crowded and as they gain confidence in the automated system. Figure 17 illustrates the potential impact on lane flow as a function of the number of people who chose to operate at Autobrake-Safegap instead of Manual-Safegap. The values chosen are only intended to be illustrative of possibilities, and tend to represent extremes in driving distance choices.

Usefulness Off the Freeway.

We see no reason that the Autogap function need be restricted to freeway use only. Operation on interstates and any relatively straight rural highways does not appear to pose particular problems.

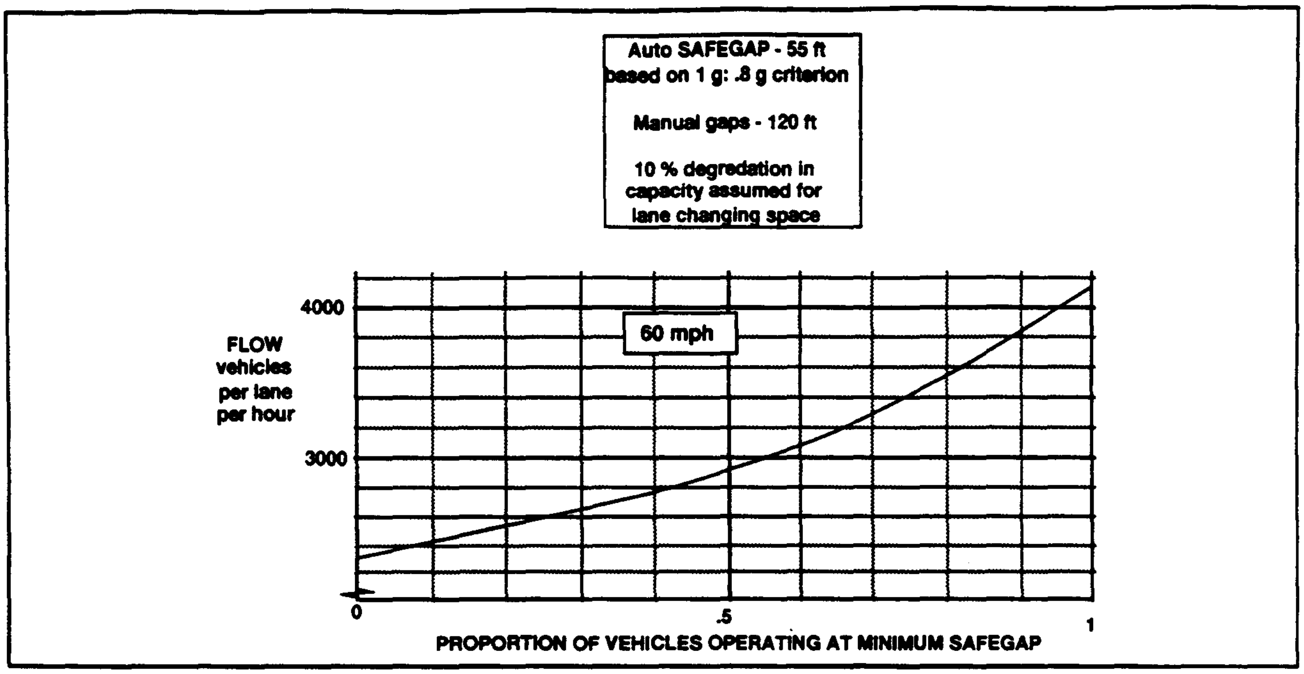

Figure 17. Potential Capacity Benefits from Gap Control

There is a problem with going around corners. If the system is to be used on surface streets, it will be necessary to provide logic to prevent unwanted behavior, either by adapting the system to the maneuver in some way, or deactivating it. This point is noted as an issue in the next section.

Developmental Issues and Risks.

Prospects for Development.

It is generally assumed that the final products that will implement AHS will be supplied by the private sector. The issue addressed here is whether the private investment can be attracted for their development.

The calculus for private sector funding is conceptually simple: there must be a reasonable prospect of future profitable return. Investment is inhibited if risk is high, or payoff a long time in coming. The cost of capital influences the acceptable time horizon.

We do not believe that marketing risk is high. If products along the lines of those described here can be offered for sale at reasonable prices, then the benefits just outlined should be sufficient to motivate purchase.

There are, however, two areas of risks that could inhibit a successful program. The first is product liability risk: there is a very real prospect that fault for many future rear-enders will be shifted by sympathetic jurors from drivers to the manufacturers of the ICC system.

The second is the uncertainty in predicting the cost of development and validation. Costs are very much a function of the technical difficulty of the tasks being undertaken. We view the technical problem of devising a sensor and sensor interpretation system that can provide the performance desired, keep false alarms to an acceptably low level, and incorporate the self-verification and failsafe features required as one that will require considerable innovation and ingenuity. And it must still result in a product at a cost that will sell. Not only are these development costs hard to predict with confidence, but in this case the difficulty is compounded by the prospect waiting in the wings of unanticipated regulatory mandates.

The public sector can play an important role in reducing these risks, and it may require the joint development now being started to produce a successful AHS. One might suggest that this should be the fundamental public sector strategy: to reduce the risks and lower the obstacles to the point that private funds could be reasonably expected to carry the program.

Robustness and Failsafety.

As discussed under Autobrake, an automatic self-test and self-diagnostic system would be an essential part of any system design. Autogap does not, as far as we can see, raise any new issues.

Operation on Surface Streets.

As already noted, the sharp turns associated with surface streets may pose problems we have not adequately thought through. They will certainly complicate the vehicle response logic, and may create requirements for additional information from the sensor/sensor-interpretation subsystem.

Potential for Retrofit.

As the system gets more comprehensive, the complexity of retrofit goes up. But we will have to be further along in design to have a basis for judgment.

Human Factor Issues.

The issue of operation in other venues than freeways raises a human factors issue. If the system is versatile enough to be left on most of the time, it is important that the driver is adequately warned to turn it off in situations where it might give unwanted responses. This implies either that the driver must remember to turn it off, or the system is able to recognize such situations, neutralize itself, and warn the driver that action has been taken.

Costs.

The observations about Autobrake generally apply here; we know too little to estimate costs. If Autobrake has already been developed, the incremental cost of adding Autogap should be small. The total costs should be minimized, however, by concurrent development.

3. THE AUTOMATIC LANE HOLDING FUNCTION (AUTOLANE) - AUTOMATIC CRUISE CONTROL

OPERATIONAL CONCEPT.

The purpose of the automatic lane hold function (Autolane) is to maintain the vehicle in the center of the lane once the vehicle has been driven manually into the lane and the Autolane system actuated. It continues to hold lane until the driver disengages the system.

Disengagement will occur at the volition of the driver. It will be necessary to configure the system to prevent accidental disengagement that could go unnoticed, but at the same time not preclude very quick resumption of manual control if some emergency warrants it. Some possibilities for meeting these criteria are described under the Human Factors section of Issues and Risks.

We consider it unlikely that Autolane will be offered for sale alone (although it could well be preceded by an Automatic Lane Deviation Warning system that does not include automatic steering). The reason for this conjecture is our difficulty in seeing the benefit to a driver just because he doesn't have to steer, but does have to maintain sufficient vigilance to continue operating the brake and throttle.

If seems much more likely that Autolane will be offered for sale only as a part of the complete package of Autobrake plus Autogap plus Autolane, a combination that could appropriately be called Automatic Cruise Control (ACC). With ACC the driver can manually drive to the desired lane for cruising, and ***turn complete control of the vehicle over to the automatic system.***

Thus the primary goal of Autolane is to offer the potential for fully automated cruise. It will also improve safety by preventing vehicles from inadvertently leaving their lane. As already noted, submode of Autolane could easily be Lane Departure Warning.

TECHNICAL DESCRIPTION.

The technical requirements hypothesized here are summarized in Figure 18 and discussed in the following.

Desired Vehicle Response - Information Needs.

The vehicle steers to stay on the centerline of the lane.

The information require for Autolane is the position of the vehicle relative to the center of the lane. It may be desirable to also measure the attitude of the vehicle relative to the centerline.

Sensing and Sensor Interpretation.

We have conjectured that one of the requirements imposed on the Autobrake-Autogap sensors is to establish which vehicles are in which lane, the implication of which is that they track the lane boundaries. Whether this information will also fulfill the needs of the Autolane system is yet to be determined. If not, then specialized sensors will be required for detecting the lane boundary lines.

Other techniques are available. The PATH program at UC-Berkeley tracks magnetic "nails" buried along the centerline of the road. Visible or RF reflectors have been suggested. There may be others.

Sensor interpretation is a less demanding problem than for Autobrake and Autogap, although it is not trivial. Almost surely an operational system will not depend on one measurement technique alone, so data fusion and reconciliation will be a requirement.

As with Autobrake and Autogap, processing must be very fast with a very low probability of persistent or bias errors.

At least some automatic steering schemes use a knowledge of road geometry beyond that derived from the on-board sensors. There are a variety of ways to acquire that information, but we make no attempt to cover them here.

The output of the sensor and interpretation system will be an error signal telling how far the vehicle is from the centerline, plus the rate of change of that signal.

TECHNICAL FUNCTIONS	AUTO LANEHOLD AND AUTOMATED CRUISE CONTROL
DESIRED VEHICLE RESPONSES - INFORMATION NEEDS	STEER TO CENTER OF LANE. NEED TO KNOW POSITION OF VEHICLE RELATIVE TO LANE, MAYBE RATE OF DEVIATION AND ATTITUDE.
SENSING AND SENSOR INTERPRETATION	REAL-TIME SENSING OF LANE POSITION. PROBABLY NEED MULTIPLE SENSORS FOR FAILSAFETY & ROBUSTNESS, SO NEED SENSOR FUSION. (MAYBE ALREADY AVAILABLE FROM AUTOBRAKE, AUTOGAP SENSORS.)
EXTERNAL INFORMATION, COMMAND INPUTS - COMMUNICATION	AUTO CRUISE CONTROL NEEDS TRAFFIC COMMANDS DIRECTLY TO VEHICLE. PROBABLY NEED VEHICLE-TO-TMS FOR EMERGENCY REPORTING.
VEHICLE CONTROL ACTUATION	ADDS ELECTRONIC STEERING (MANUAL CONTROL EITHER MECHANICAL OR ELECTRONIC.)

Figure 18. Auto Lanehold Mechanization: Functional Description of Technical Elements Required

External Information & Command Inputs - The Need for Communications.

All traffic commands will go directly to the vehicle. introducing the almost unequivocal need for communication from the Traffic Management System (TMS) to the vehicle. The "deadman problem" may also require signals from the TMS; this is discussed later.

Additionally, there will probably be a need for malfunction alerts from the vehicle, so two way communication becomes a highly probable requirement.

Vehicle Control Actuation.

Autolane brings in the third element of vehicle control, and introduces the need for electronically actuated steering.

There is a serendipitous byproduct to a drive-by-wire capability now that we have electronic steering in all three vehicle controls. Now it becomes technically feasible to begin considering new or substantially modified approaches to manual control. We are still using today techniques of control that were derived from the original need to use human muscle to steer, brake, and control the throttle. With that constraint gone, the manual controls could be designed differently if there appeared to be advantages in doing so, and if failsafety concerns could be dealt with.

Infrastructure Modifications.

The point has already been made that fiducial marks of some kind will be necessary to permit orientation of the vehicle relative to the lane. It is believed that these will be simple enough that they can be installed relatively inexpensively and with little disruption.

System Mechanization.

The system mechanization is shown in Figure 19. It can be seen that the basic architecture is unchanged, just incremental modifications. Given standardized interface specs, there is substantial freedom for technical innovation in the individual subfunctions.

Potential Benefits - Motivation to Purchase.

Driver Convenience.

We conjecture that Automatic Cruise Control would be a boon to anyone whose commute involves even a moderately long freeway segment, or anyone who does much intercity traveling. ACC could take much of the strain and boredom out of long trips.

Safety.

While the primary motivation for purchase might be driver relief, ACC should also offer another increment in improved safety: the essential elimination of wandering out of the lane or off the road for any travel on equipped highways. The sleepy driver threat is essentially nullified.

Usefulness Off the Freeway.

We have already alluded to the fact that ACC should be usable on any freeway or highway that has the lane markings and other modifications required to accommodate Autolane. But it is improbable that ACC could be used on surface streets without integration with the Traffic Management System.

Developmental Issues and Risks.

Prospects for Development.

The prospects are quite good if the ICC appears to be fulfilling its promise. The liability hurdle has been passed with the introduction of Intelligent Cruise Control, and the most difficult part of the sensor interpretation problem apparently solved.

Robustness and Failsafety.

As already noted, an automatic self-test and self-diagnostic system would be an essential part of any system design. The addition of Autolane and its integration into a comprehensive Automatic Cruise Control system does reemphasize the need for a

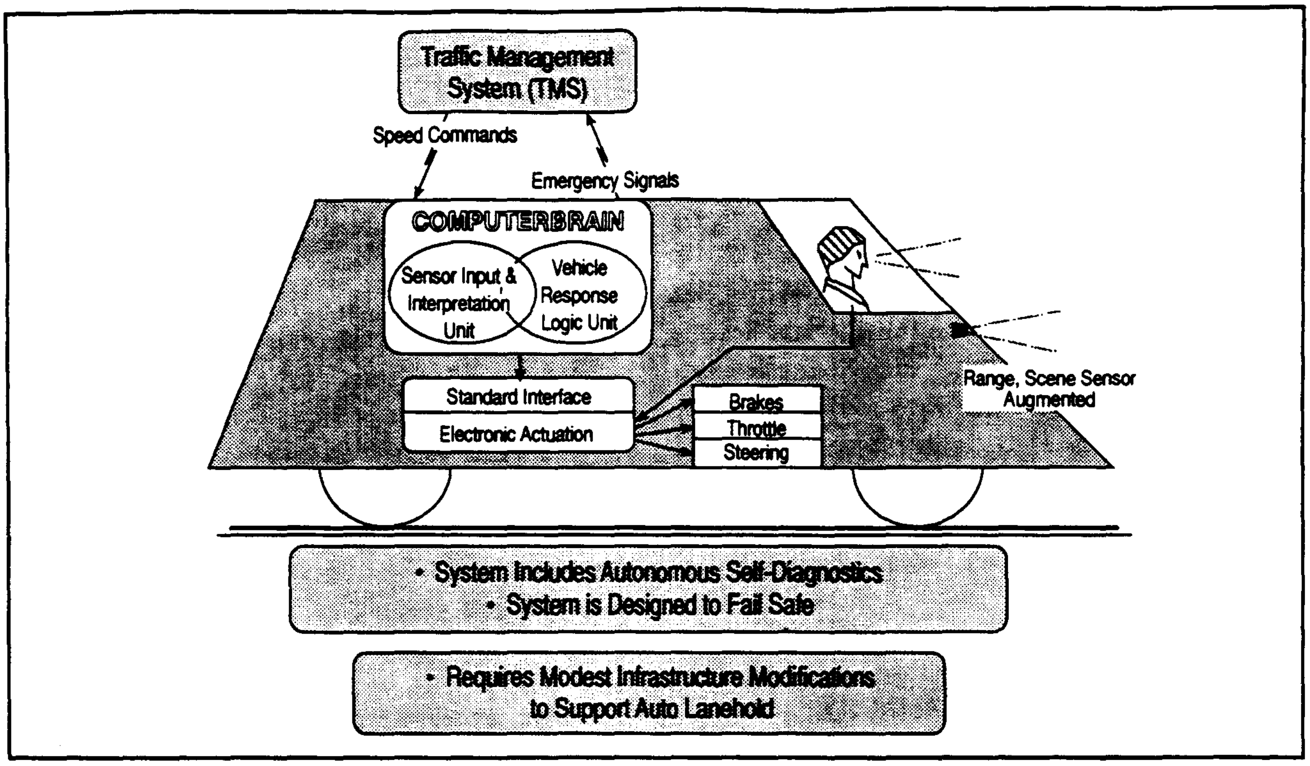

Figure 19. Adding Auto Lanehold: Automated Cruise Control Hands-Off Freeway Cruising – The Mark I AHS

carefully designed and comprehensively tested Integrity Verification Subsystem.

The failsafety-failsoftly problem is now more complex than with only Intelligent Cruise Control, and will require even more careful consideration; this is discussed under Human Factors, following.

Vehicle Behavior Algorithms.

It is our belief that there will be no important interactions between the steering mode and the drive-train control mode, so that the addition of the lateral control channel will not dictate the need for change in the Intelligent Cruise Control algorithms.

Other System Areas.

Electronically actuated steering is already in extensive test, and its addition should not pose unusual problems. More sensors are required, but they are well within the state-of-practice.

Potential for Retrofit.

The prospects look dimmer and dimmer.

Human Factor Issues.

ACC does introduce new human factors considerations that go beyond the proper design of controls and displays. With only Intelligent Cruise Control, the driver was still required to watch the road and the general driving situation in order to steer; ICC merely relieved him from the frequent braking and acceleration otherwise required. While this may have permitted some relaxation in vigilance, the driver was still in a position to take immediate manual control of the vehicle in the event of an emergency.

Automatic Cruise Control removes the motivation - if not the need - for driver vigilance. The implication is that the driver may not only take longer to react to an emergency or an unusual situation, but may also be in a mental state that is not conducive to an immediately rational response. This problem will require attention.

It has already been noted that will be necessary to configure the system to prevent accidental disengagement that could go unnoticed, but at the same time not preclude very quick resumption of manual control if some emergency warrants it. The temptation to have the driver reassume steering control by just turning the steering wheel slightly is precluded by the first constraint, yet substituting too complex a procedure violates the second.

Perhaps something along the following lines. Small manual inputs to the steering wheel do not disengage the system unless the driver has already set the "Off" switch. But a vigorous steering wheel input immediately gives control to the driver. Obviously it would take considerable testing to validate this or any other approach, and obviously there are many variants of such schemes that will require evaluation.

A DIGRESSION: DEPLOYMENT AND THE DYNAMICS OF COST BEHAVIOR

Thus far we have hypothesized two major deployment steps. The first was the introduction of Intelligent Cruise Control (ICC), which included a full-time Autobrake system and an integration of conventional cruise control with the new Autogap function.

The second step was the addition of the automatic lane holding function, Autolane, producing a system capable of fully automated, hands-off cruise on any freeway, highway, or road modified to support Autolane. We called this system Automatic Cruise Control (ACC). It is, in fact, the Mark I version of the Automated Highway System.

The rate of deployment of these systems will hinge very importantly on their costs, but development is not far enough along to be able to estimate these costs with any confidence. Neither do we have any useful intuition about the demand curve - the relationship of number of sales to prices. But it is possible to illustrate at least one aspect of the problem: the change in costs as deployment progresses.

The central player is the so-called "experience curve". The experience curve describes the predictable reduction in production costs as a function of the number of units produced. It is a phenomenon that has been observed in many industries, and has been well established by empirical data. It is a consequence of both learning to make the production process more efficient, and incremental improvements in technology and design to make it easier.

These data reflect the fact that unit costs typically vary as an exponential of the total number of units built. Specifically, it implies that production costs reduce by some fixed percentage every time the total number of units built is doubled. As an example, a 90% curve implies that the second unit produced would cost 10% less than the first, the 20th would cost 10% less than the 10th, and the 200,000th would cost 10% less than the 100,000th.

The experience curve is central to the pricing strategy of many companies, and it is reasonable to think that it will be extremely important to the future of the AHS, as the following illustrates.

Figure 20 is a purely conjectural assumption about the rate of diffusion of ICC and ACC as a function of time: it shows the hypothesized cumulative number of equipped vehicles over the first ten years after initial introduction. In drawing these curves we have assumed that once the fully automated capability of ACC is available - here shown five years after the introduction of ICC, ACC will begin to almost fully displace ICC.

These curves are in no sense a forecast, but a mechanism to illustrate the behavior of costs over time. Within broad limits, this behavior is relatively insensitive to the particular values shown: we could double them or halve them without affecting the basic phenomena we wish to illustrate.

The top of Figure 21 repeats the cumulative sales chart of Figure 20. The plots at the bottom show the production costs of one unit at the beginning of each year of production (we assume production equals sales). In constructing Figure 19 we have arbitrarily assumed that the first production model of an ICC will cost $10,000, and that unit costs thereafter will decrease along a 90% learning curve.

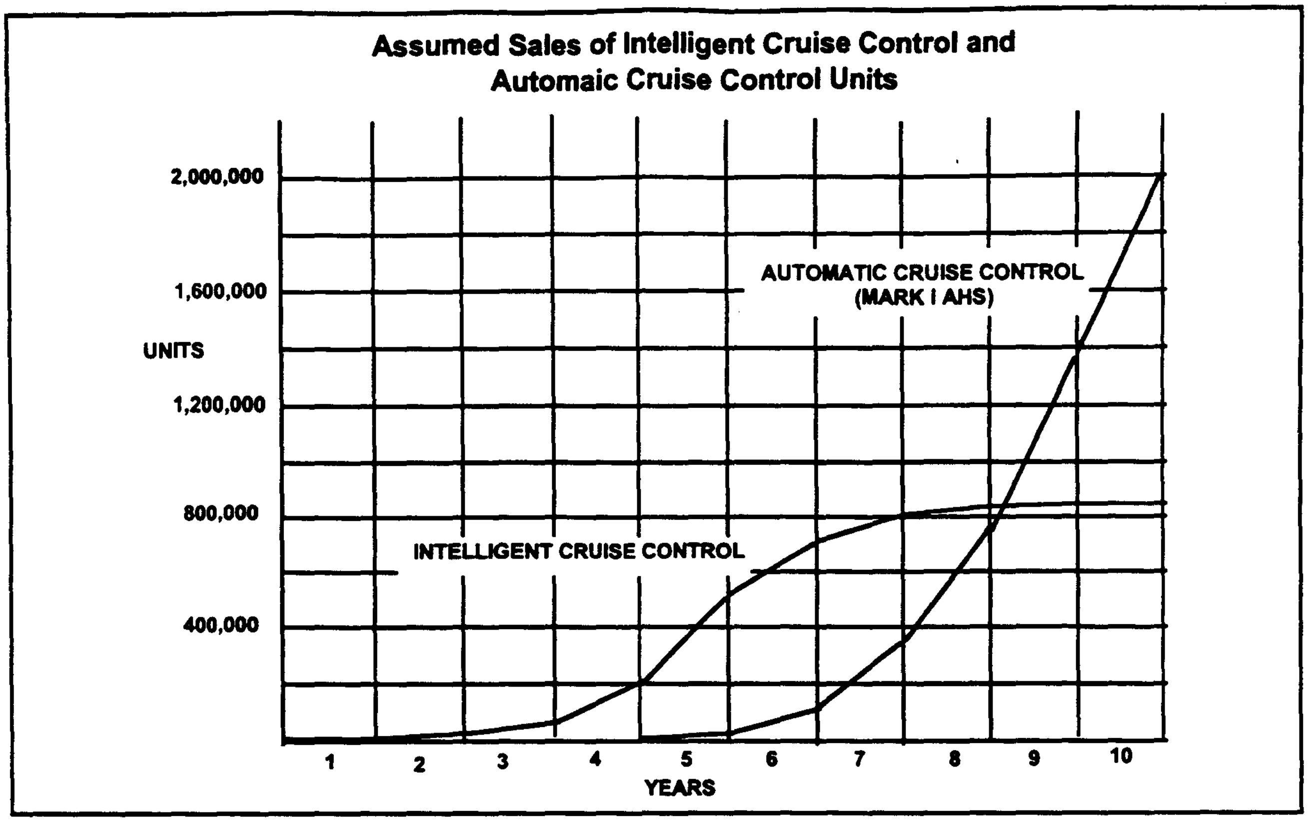

Figure 20. An Illustration of the Dynamics of Cost Behavior - I

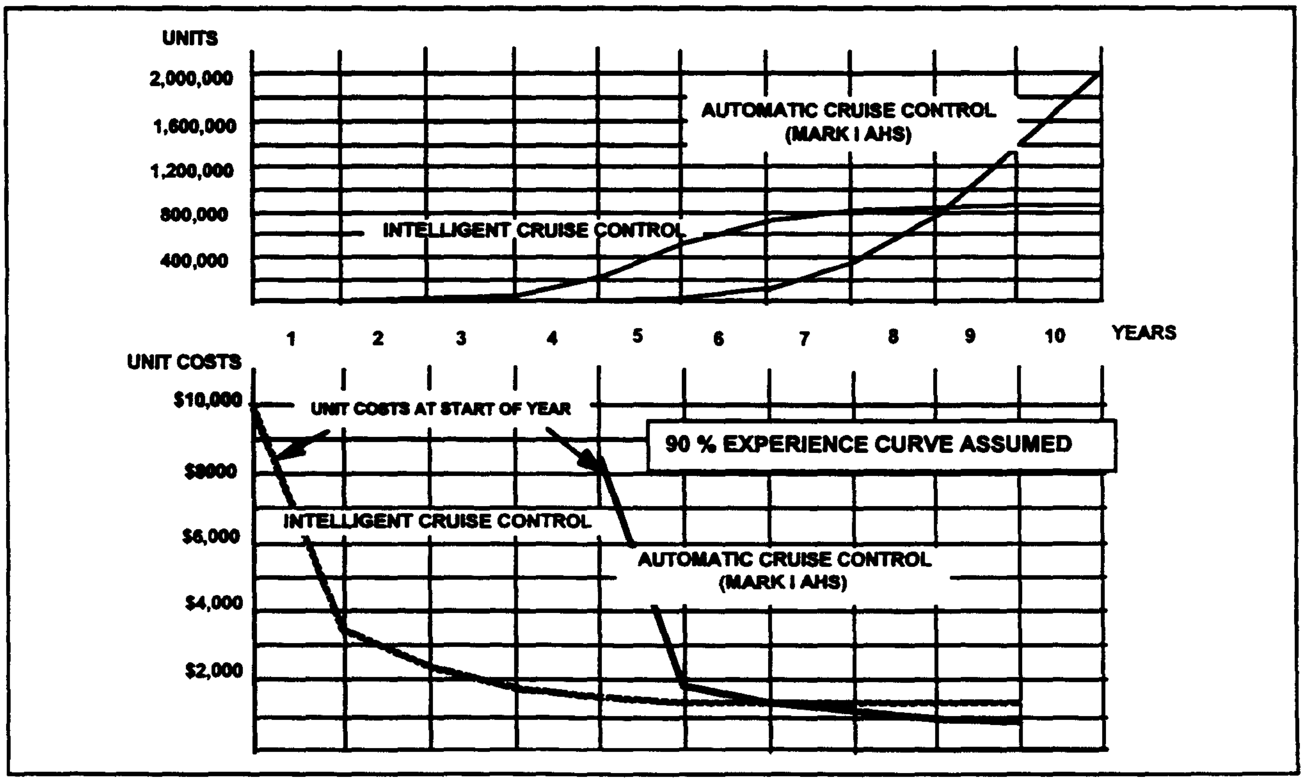

Figure 21. An Illustration of the Dynamics of Cost Behavior - II

Since ACC builds on ICC, we have also assumed that the initial production model of ACC - here shown five years later - will be less expensive at $7500. We have used these assumptions to calculate how costs will vary over time as deployment proceeds along the paths assumed in Figure 20.

As can be seen, costs drop very rapidly in the first year, but as more units are produced, the doubling time increases so costs come down more slowly. But they come down significantly: over the total of 872,000 ICC units produced the unit production costs drop from $10,000 to $1,250 for the 90% experience curve assumed. Over the 2,000,000 ACC units assumed, the unit production costs drop from $7,500 to $827.

For pricing purposes, the cumulative average costs of production may be more relevant than the unit by unit costs. In Figure 22 we show the average unit production costs as a function of the number of units produced.

Figure 22 also illustrates a second, and more important, point: the extreme sensitivity of costs to the slope of the experience curve. For the largely solid state technology that we anticipate for AVCS and ACC, slopes of 85 percent or lower are a reasonable expectation.

We will go through a hypothetical - and simple minded - pricing exercise for ICC. Let us assume the manufacturer believes that an 85% experience curve can be achieved, that he can sell at least 500,000 units, that he wants to recover $150,000,000 investment in development by the 500,000 unit, and that he wants a 10% margin over these total costs to cover marketing and other associated overhead. From Figure 22, the cumulative average unit costs at the 500,000th unit are about $600, and the unit share of the development costs are $300. This gives a total cost of $900, which with a 10% markup gives a sales price of $990. Sales at this price beyond the 500,000 level become profitable, particularly if the $150 million now recovered represented all of his

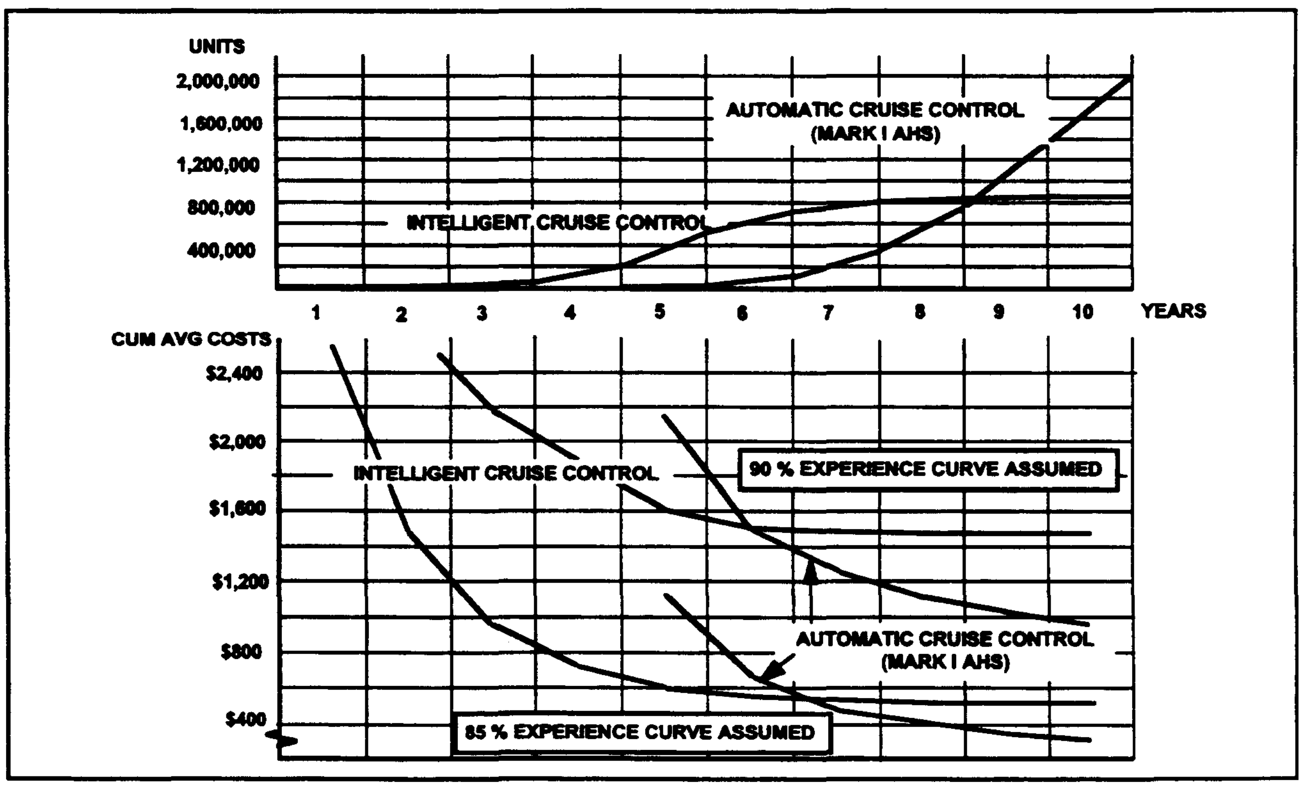

Figure 22. An Illustration of the Dynamics of Cost Behavior - III

development costs; in that case the $990 includes a gross margin of 33%.

Will 500,000 people buy ICC at this price in the first five years? We think yes. Are our assumptions about experience curve slopes and initial production costs reasonable? We don't know. Can ICC - self-check, failsafety and all - really be developed and thoroughly tested for $150,000,000? Probably not. But we know what to begin to think about.

4. THE SPONTANEOUS PLATOONING FUNCTION (AUTOPLATOON) - ADVANCED AUTOMATIC CRUISE CONTROL

Operational Concept.

The operational concept put forward here differs substantially from the notion of platoons of vehicles forming up off-freeway, going through some check-out procedure, entering the freeway and then proceeding as a unit to their common off-ramp.

The operational concept hypothesized here, based on the notion of spontaneous platooning, was first articulated to us by Dr. Loren Clare of the Rockwell International Science Center. His basic idea was that of a self-organizing system, a system which spontaneously reorganized itself to continuously adapt to its changing operating environment.

We begin at the beginning: the purpose of platooning is to increase the effective capacity of the freeway. It accomplishes this by reducing the normal separation between some vehicles from perhaps 50 to 100 feet down to 2 or 3 feet, thus freeing up space that can accommodate additional vehicles. Put in mathematical terms, it increases the density of vehicles without the necessity of changing speed to maintain safety.

(A glance back to Figure 7 illustrates that cruising with a spacing of 2-3 feet is essentially as safe in terms of longitudinal collision velocity as the safegap at the other end of the curve.)

We would like to platoon only when the additional freeway capacity it provides is actually needed. We therefore would like to initiate platooning only when the density of vehicles approaches the capacity limit (maximum flow accommodation) of the freeway at the existing speed. When that point is approached the need for platooning is signaled, and some of the vehicles equipped for platooning that are adjacent to other equipped vehicles automatically move to platoon.

As vehicles desire to leave the lane, the drivers signal their intent to resume manual control and the vehicles automatically deplatoon, permitting the driver to take over and drive out of the lane. As vehicles leave the lane, the need for platooning decreases, allowing additional deplatooning.

The principles of spontaneous platooning have been simulated extensively, and have clearly demonstrated the ability of vehicles to self-organize into platoons as the traffic flow demand increases, and to deplatoon when demand decreases.[2]

The trick is how to make the decision to platoon or to deplatoon in response to changes in the demand. Some of the possible techniques are briefly discussed in a special section below: The Platooning-Deplatooning Decision.

The Platooning-Deplatooning Decision.

One can think of three basic approaches to making this decision.

The fundamental assumption behind the first two approaches outlined here is that as more vehicles enter the lane, vehicles drive closer together until some minimum spacing is reached, at which point some drivers begin to slow down. The result, of course, is that the whole traffic stream is forced to slow correspondingly. This suggests two possibilities for inferring the level of congestion:

- First, measuring the gaps between vehicles to directly measure vehicle density, and use this value to determine when the platooning process

[2] J. Agre and L. Clare, "Spontaneous Platooning: A Self-Organizing Approach to Improve Flow Capacity", Presented at the Third Annual IVHS America Conference, Washington D.C., April 1993.

should begin. The advantage of this approach, if we can make it work, is that it forestalls the need for traffic to slow.

- Alternatively, wait until speed change actually occurs as a sure signal that maximum capacity at the original speed has been exceeded. This latter approach has the advantage of being much simpler to implement than the density approach.

Every equipped vehicle is measuring the gap in front, and is able to communicate to any adjacent equipped vehicle. One operational scheme to exploit this basic idea of measuring the gap to infer incipient congestion is to have each vehicle communicate the gap it is measuring up and down the line of traffic, flagging those readings from vehicles in the midst of lane-changing or platooning-deplatooning maneuvers. There would be some limit on how far the sampling should extend from each car - two vehicles?, four vehicles?, ten vehicles?. Thus each vehicle would have a value for the local vehicle density, with which it could use the equivalent of the highway capacity curves to make the platooning-deplatooning decision.

There are at least two problems with this scheme. First, when only a small proportion of the vehicles are equipped, the sample with be truncated when the communication hits an unequipped vehicle. Perhaps it doesn't matter, because there is little need for precision, and, as will be shown, the gain from platooning is small until about half the vehicles have the spontaneous platooning feature added to ACC (which we call Advanced ACC).

The second difficulty is that the gap in front of each vehicle represents the choice of the driver when he or she adjusted Autogap, and may or may not reflect the level of congestion. The seriousness of this problem depends on how most drivers react to other vehicles entering the lane in front of them. If vehicles repeatedly enter - in itself a signal that there is a need for more capacity - some drivers at least close up the gap to discourage new entrants in front of them. If most drivers react this way, then the gaps may become a reasonable reflection of the state of congestion and demand.

The second approach noted above, in which changing speed signals the need for platooning, was to let high density manifest itself through decreasing stream speed, and let this be the trigger to initiate platooning. This is much less ambiguous than the approximate-density-measurement approach, and certainly easier to implement. This is the technique used in the simulations described in the Agre-Clare paper. It works.

It is probable that some combination will finally evolve as the preferred approach. If each vehicle was counting the rate of intrusions - or the surrogate, the small speed loss if the car was forced to slow because of the intrusion - it might be possible to infer a combination of conditions that are a reliable guide to platooning. The wide variety of possibilities will require much more in-depth thinking and simulation.

There is also a basically different approach to the problem: rather than leave platooning to some form of distributed decision made by the individual cars, it could be turned over to the Traffic Management system (TMS).

For example, when the TMS observed congestion rising, it could broadcast a start-platooning signal to all vehicles in that segment of the freeway. It may not be required for all eligible vehicles platoon, so some scheme to do it in steps might be preferable. For example, have one-fourth of all platoon-capable systems sold sensitive to A-signals, one-fourth to B-signals, and so on. This time TMS sends a B-signal, so all B-vehicles automatically platoon with the nearest equipped vehicle, whether it be A, B, C, or D. This results in something less than half the equipped vehicles joining in two-vehicle platoons; the B-B combinations and the Bs not next to an equipped vehicle keep the total below one-half. Still more congestion causes the TMS to send both B and D signals. And so on. This scheme removes the spontaneity from the decision, but retains the autonomous action in forming and dissolving platoons. (It also may be an important tool of velocity-flow control to cope with flow interruptions, but that is another subject.)

Once the basic decision is turned over to the Traffic Management System, one can think of other variations. One possibility is to postpone, and possibly forestall, the need for platooning. A signal broadcasted into the segment of the freeway that was beginning to congest, for example, could take gap control away from the driver, and have all equipped cars close the gap to safegap - the minimum safe gap at that speed with the automatic system operating. As noted before, this would reduce the gaps at 60 mph from a driver-chosen 100 or so feet to less than half that. Figure 12 characterized the potential gain from this approach.

TECHNICAL DESCRIPTION.

Figure 23 summarizes the technical profile for Autoplatooning. Briefly, there are only three changes from the requirements for Automatic Cruise Control:

1. Vehicle-to-vehicle communication is required between adjacent vehicles in the same lane.
2. The range of accurate distance and rate of closure measurements is extended to close distances: down to a foot or so.
3. The vehicle response algorithms must be extended to control platoon formation, cruise in the platooned state, and deplatooning. If the algorithms require information beyond that available from currently-defined on-board measurements, then a source for that information will also be needed.

It is even more probable than with ACC that communication from the Traffic Management System to the vehicles will be needed; the circumstances are discussed further in the following.

The individual elements in the system mechanization are discussed in somewhat more detail below.

Desired Vehicle Responses - Information Needs.

The vehicle response controller must now include the dynamics of the platoon formation maneuver, the steady-state platooning during cruise and during speed changes, and the deplatooning maneuver.

Possibly the most demanding new requirement is providing the basis for the decision as to when platooning or deplatooning is desirable; this has already been discussed.

Sensing and Sensor Interpretation.

The same information required for Autogap is required for platooning, but the range of interest must now be broadened down to platooning distances. Further, platooning demands more precision in position control than Autogap, so the continuity and increment thresholds in measurement must be commensurate.

It is possible that platooning will require new sensing, but we do not now foresee that need.

External Information & Command Inputs - The Need for Communications.

Both platooning and the platooning-deplatooning maneuvers require coordination of control actions between the involved vehicles, so communication between these vehicles is required.

Further, in order to count the vehicles in a platoon, and perhaps to pass on information relevant to the spontaneous platooning decision, it will probably be necessary to have a relay capability and a means of identifying the source of original message.

Last, if the platoon-deplatoon decision is relegated to the TMS, communication from the TMS to the vehicles will be required.

As with ACC, it should be possible for the Traffic Management System to vary the stream speed by communicating commands to the ACC-equipped vehicles, and for communication from vehicle-to-TMS for May Day signals if the driver fails to retake command of the vehicle.

Vehicle Control Actuation.

These are the same as for ACC, except the precision of control during platooning is more demanding. This requires more vernier control than with ACC.

TECHNICAL FUNCTIONS	SPONTANEOUS PLATOONING
DESIRED VEHICLE RESPONSES - INFORMATION NEEDS	LIKE AUTOGAP, DEGREE OF BRAKING AND ACCELERATION - BUT FOR MORE VERNIER CONTROL THAN AUTOGAP REQUIRES. MUST CONTROL DYNAMICS OF PLATOON FORMATION AND DEPLATOONING.
SENSING AND SENSOR INTERPRETATION	SAME AS AUTOGAP, BUT PERHAPS BETTER ACCURACY AND MORE SENSITIVE INTERPRETATION AT CLOSE RANGE.
EXTERNAL INFORMATION, COMMAND INPUTS - COMMUNICATION	• VEHICLE-TO-INFRASTURCTURE SAME AS AUTO CRUISE CONTROL. • VEH-TO-VEH REQ'D TO COORDINATE CONTROL ACTIONS WITH VEHICLES FORE AND AFT.
VEHICLE CONTROL ACTUATION	VERNIER CONTROL OF BRAKES AND THROTTLE

Figure 23. Spontaneous Platooning Mechanization: Functional Description of Technical Elements Required

System Mechanization.

The mechanization architecture is illustrated in Figure 24; the only change is the addition ofVehicle-to-Vehicle communication.

POTENTIAL BENEFITS - MOTIVATION TO PURCHASE.

Capacity.

The basic reason for adding a platooning capability to an ACC system is to increase the effective capacity of the freeway. This, in a sense is a substitute for the expense and environmental impact of additional concrete. As is discussed below, this fundamental motivation may or may not be persuasive to the individual driver.

Figure 25 illustrates the fundamental phenomenon that motivates platooning. Without changing a given safe spacing, platooning increases vehicle density. Since flow is the product of density and speed, platooning increases the flow potential at any given level of safety (almost - see the discussion of safety following).

As can be seen in the figure, the maximum lane capacity depends on both the size of the platoons and the spacing between them; the influence of platoon size is increasingly important at larger spacings. As we have already noted, the spacing that is safe depends on the speed of the system and the relative braking capability of the vehicles involved.

Platoon size is an analytically more complex issue. As already described, platooning can only occur when both vehicles are equipped with the Autoplatoon feature. Under the assumption that Autoplatoon vehicles are randomly scattered among non-Autoplatoon vehicles, the level of platooning is very low when few vehicles are equipped, and rises as higher levels of equipping increases the probability of contiguous equipped vehicles. As more vehicles can platoon, both the average and the maximum platoon sizes increase.

Under the spontaneous platooning concept, the size of platoons is also strongly influenced by the proportion of vehicles of vehicles entering the lane relative to those leaving at each ramp location. Platoon size is thus determined by the proportion of vehicles with the Autoplatoon feature, and the

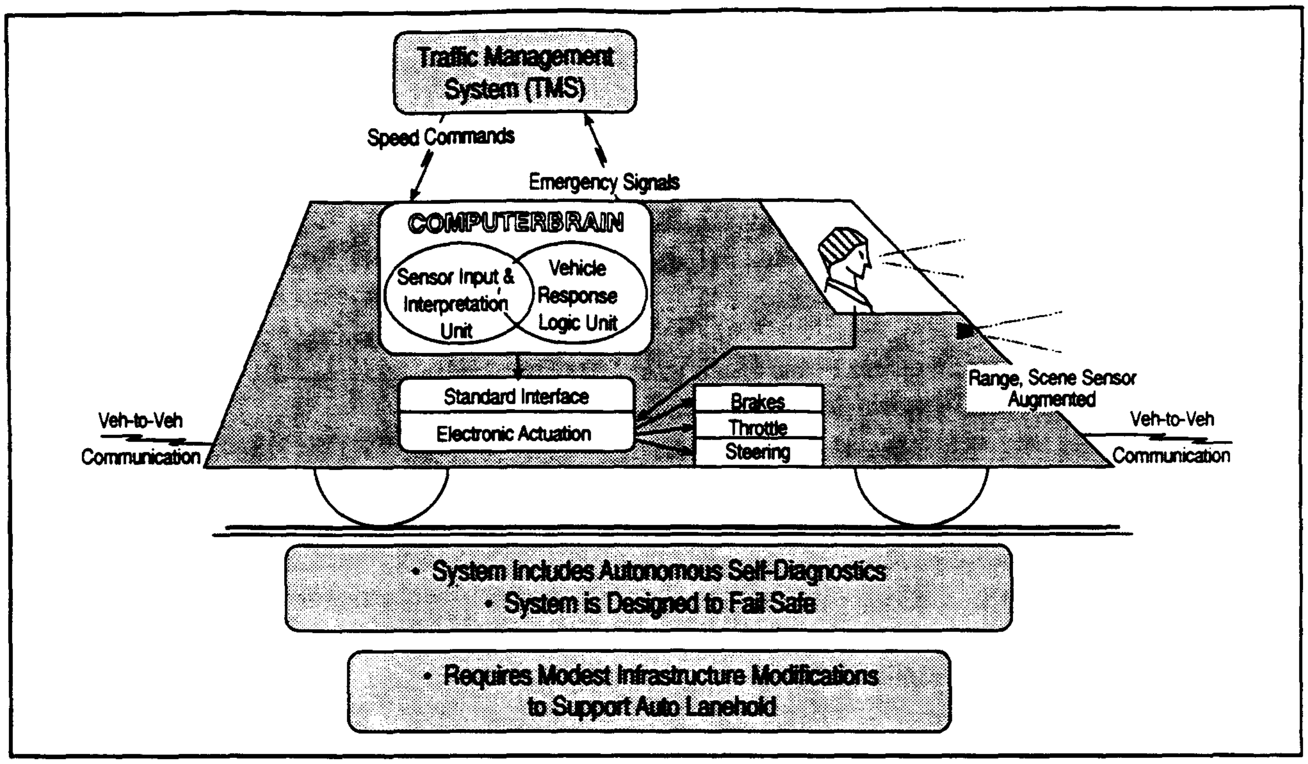

Figure 24. Add Spontaneous Platooning: Advanced Automated Cruise Control

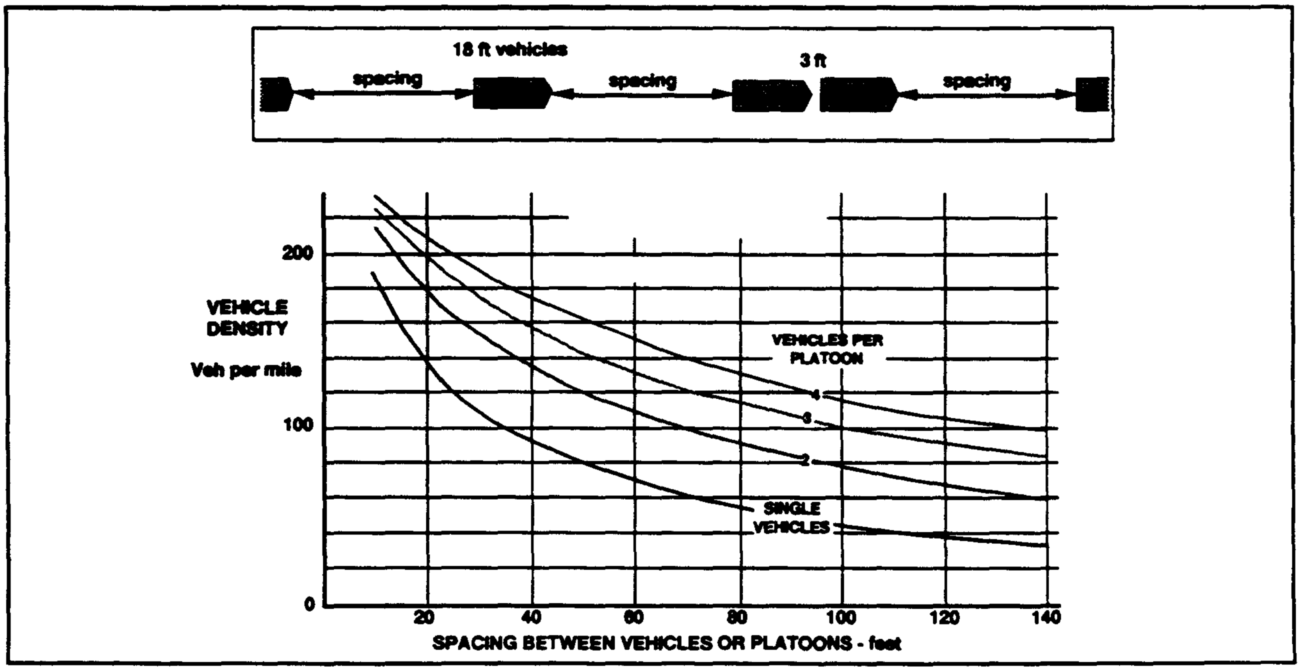

Figure 25. Density, Spacing, and Platooning Relationships

dynamic balance between the number vehicles entering the lane and potentially adding to platoon size, and the number leaving which force them to break apart. When these latter numbers are in balance, very few platoons will ever get above two or three vehicles.[3] When more vehicles are entering than are leaving, platoons will get larger unless they are constrained to some specified maximum.

Figure 26 shows the variation in lane flow as a function of the percent of vehicles equipped with Autoplatoon. These curves include both the effects of decreasing average "safegap" and increasing average platoon size with the proportion of equipped vehicles. The maximum platoon size is constrained to 4 vehicles. The speed effect is mitigated by the fact that safegap increases with speed, and maximum flow is apparently peaking around 80 mph.

For the conditions shown here, the proportion of cars exiting at each ramp has little impact on maximum flow, but, as will be shown later, it does impact the distribution of platoon sizes.

One of the simplifying assumptions in the computations of Figure 26 was the omission of any extra lane space to permit entry and exit maneuvers. It is not clear to us today whether extra space is really needed, but prior calculations - more conservative on this issue - would suggest that this omission results in overstating the maximum flow by as much as 15 percent.

Figure 27 shows the distribution of platoon sizes for two different levels of exiting. As expected, more exiting breaks up more of the larger platoons, thus changing the distribution of sizes, but because the broken 4-vehicle platoons add to the number of smaller platoons, the overall impact on flow is dampened.

While we believe the trends shown in Figure 27 are valid, we have less faith in the specific numbers because of simplifying assumptions made in the calculations. These computations and the major assumptions are described in Appendix A.

Driver Motivations.

The addition of the spontaneous platooning feature to Automatic Cruise Control offers no new relief from driving chores. Further, it will take some getting used to: people are not accustomed to driving only three feet or so from the next vehicle.

The effective capacity increase just discussed is, in itself, a dubious motivation. The argument can be that, in fact, drivers will perceive only negatives from platooning, that the primary beneficiaries of this extra capacity are the additional cars coming into the lane, not the drivers already there who are doing the platooning.

There is an alternate perspective, based on the notion that the consequences of platooning is less to make room for more cars than it is to maintain reasonable speeds in spite of more cars entering the lane. In this perspective the platooner is directly benefiting from his or her vehicles' action through reduced congestion. It is true that he or she is not the only beneficiary, which may dilute the motivation to be the one who does the platooning.

The difficulty with this latter perspective is that increasing effective freeway capacity is unlikely, by itself, to reduce congestion, simply because growth in demand will probably outstrip growth in capacity. If demand outstrips capacity, then congestion itself allocates freeway space, and cars will continue to enter a freeway until traffic is already severely slowed - no matter what the capacity level.

An actual reduction in congesting will require some form of demand management, like more stringent metering or road pricing. The additional capacity means that the queues do not have to be as long or the price hurdle that permits entry to the freeway doesn't have to be as high because it is not

[3] J. Ward, "The Contribution of Platooning to Increased Freeway Capacity", Presented at the First Annual IVHS America Conference , Reston, VA, March, 1991.

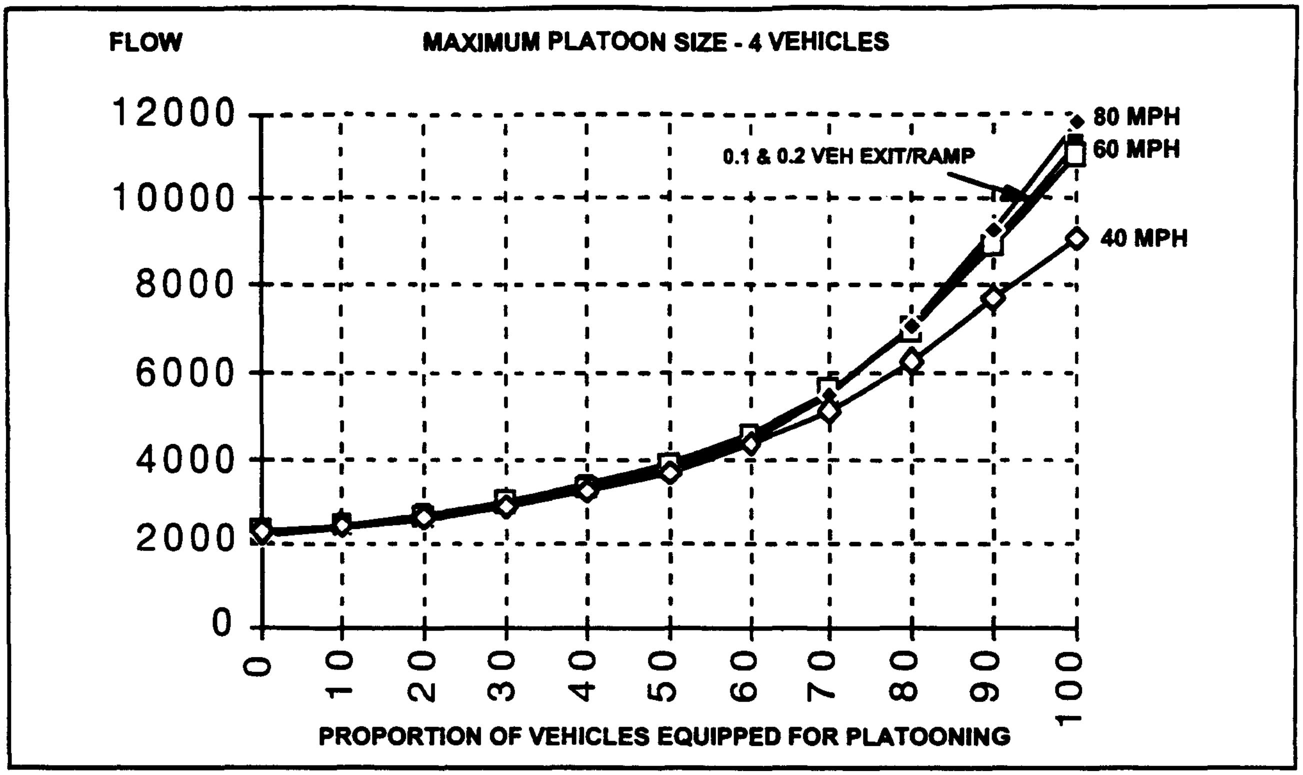

Figure 26. Lane Flow as a Function of Proprortion of Vehicles Equipped with the Autoplatoon Feature

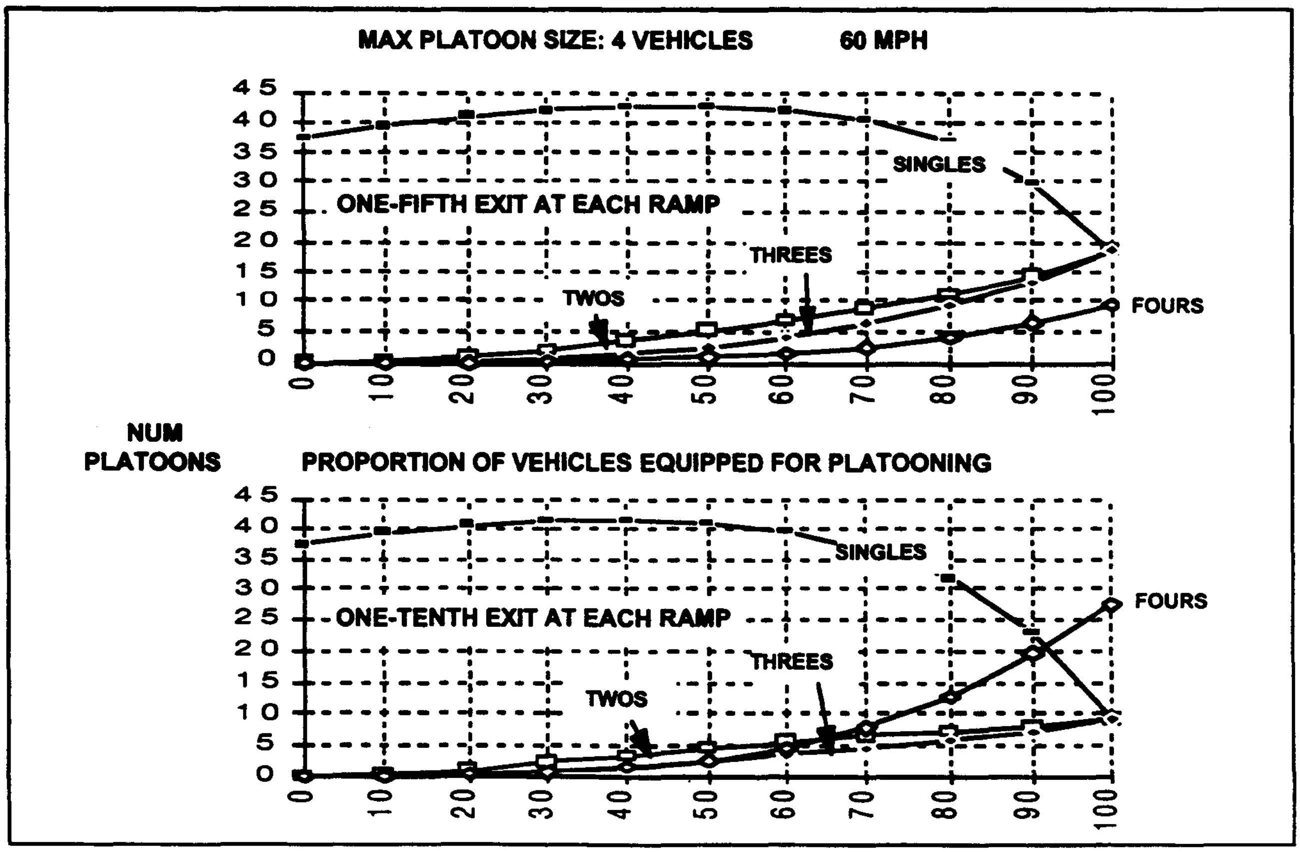

Figure 27. Variation in Platoon Size Mix with Proportion Equipped

necessary to discourage as many vehicles. But it is unclear whether drivers who would prefer not to platoon will ultimately perceive the benefits of doing so anyway.

The clearest beneficiaries are the public at large who don't have to tolerate or pay for new freeways because of the effective capacity gains of those already in place. It is just not clear how the individual driver will view the system.

Safety.

Spontaneous platooning introduces some penalty to safety. There are two sources. The first is the obvious one of driving close: while the collision velocity between the two adjacent vehicles is too low to be unsafe, there is always the possibility, however small, that lateral forces - or a lateral collision from another vehicle - could cause a general pile-up; this is an obvious incentive to keep the size of platoons small.

Second, there is some new risk added from the closing-to-platoon and the opening-to-deplatoon maneuvers. Figure 4 shows that while being close is safe and being beyond safegap is safe, in between is not. To perform these maneuvers vehicles will have to cross through these unsafe spacings. While system design will be such as to reduce the risk to almost zero, the "almost" may be small, but it won't be zero.

There is a trade between safety and capacity in this concept. We believe that platooning can be mechanized to actually improve net safety and still significantly increase effective capacity. But evaluating this trade is beyond the scope of this paper.

Summary. Withal, it appears that the motivation to equip one's vehicle with the ***Advanced*** Automatic Cruise Control system capable of spontaneous platooning is less than it has been for either ICC or ACC. One can think of two approaches for increasing that motivation. First, it may be rational to pay people to equip their cars with the ACC with Autoplatoon, rather than just ACC, since it substitutes for more road surface.

Second, it may be justifiable to require that all ACC systems sold beyond some date include Autoplatoon. This would cut the Gordian knot on motivation to equip for platooning, just as the scheme based on TMS control of the platooning decision cuts the Gordian knot on who, when, and where platooning takes place.

Usefulness Off the Freeway.

Platooning should be useful on some crowded interstates. The issue of its practice on surface streets will require more investigation; at the moment it appears dubious.

DEVELOPMENTAL ISSUES AND RISKS.

Prospects for Development.

The problem here is sorting out who benefits, who pays. The ambiguity in motivation to purchase will cast doubt on the market potential in the eyes of private developers. And if the Traffic Management System is made part of the decision to platoon, then there is a need for compatibility with a public sector owned and operated system. We cannot predict with confidence that this enhancement to ACC will be viewed as a good use for private capital.

Since, however, platooning is a substitute for additional concrete, there is justification for either public subsidy or even public mandate.

Robustness and Failsafety.

As always, the Integrity Verification Subsystem - the self-test and self-diagnostic system - will be an essential and integral part of the system.

Vehicle Behavior Algorithms.

Working out the best way to handle the platoon-deplatoon decision process is one new element in the development. The second is the control of the dynamics of the maneuvers themselves, including steady state cruise in the platooned position.

These classify more as work that will have to be done than technical risks. There is nothing here that pushes the state of the art.

Potential for Retrofit.

Highly unlikely.

Human Factor Issues.

The primary one is the acceptance of the close proximities platooning implies. This is clearly daunting now: how much it will continue to be after a few years with ACC remains to be seen.

PART III.

SUBSEQUENT EVOLUTION OF AHS AND AUTOMATED VEHICLE CONTROL

The evolution hypothesized so far carries us to fully automated cruise in a freeway or highway lane. Entry to and exit from the lane are under manual control, as is all operation on surface streets. In this Part III, we sketch some possibilities for subsequent evolution.

AUTOMATIC LANE CHANGE

We conjecture that the next step in evolution is the addition of automatic lane change on freeways and highways.

There are at least two justifications for the function. The first is safety: we have noted before that there are occasions when even full emergency braking cannot prevent collisions, leaving the only other option to pull out of the lane to go around the object. Performing this maneuver automatically will be considerably faster than depending on driver reaction.

The second justification is the aging of the population and the desire to make driving safer for the older driver. Having automatic lane change opens the possibility of having the complete freeway trip mechanized, so the driver need only drive the car to the on-ramp, and take control again after exiting the freeway. The driver would have identified the desired exit lane, and the vehicle would navigate to it using either on-board navigation or by detection of identifying signals from the road itself.

The mechanization of automatic lane change is, like all those hypothesized so far, autonomous, and insofar as we can envision now, requires no communication with the Traffic Management System other than that already available with Automated Cruise Control. The vehicle will require more on-board information gathering, however, because it will be necessary to monitor conditions in the receiving lane to insure safety. The top level mechanization is shown in Figure 28.

Next Steps. It is unclear what might happen next. We can think of two not-mutually-exclusive possibilities. The first is a dramatic increase in highway cruise speeds. The other is to extend automatic control to surface streets. This latter is a very important step - or series of steps - that could open up a whole new world for urban transportation.

SUPERCRUISE

The motivation for increased intercity cruise speed is reduced travel time. Higher speed will increase the trip length at which air becomes the dominant mode, and increase the demand for highway travel both by this modal shift effect and by inducing new travel. The impact will be similar for the movement of high value freight.

The advent of higher highway speeds are likely to induce changes in the competitive air and rail modes. In heavily traveled corridors, such a move on the highways may well precipitate new high speed ground systems that would serve both freight and passengers. It is beyond the scope of this study to examine these consequences, or the net impact on demand for highway travel.

Markedly increased speeds introduce two new technical and operational problems. First, it would necessitate a substantial increase in the range of the sensors in the Intelligent Cruise Control system. Second, it opens new issues about the modus operandi for controlling access to the high speed lane. It emphasizes the need to protect the lane against foreign intrusions of any kind, and may pose the need for physical barriers. Developing a workable operational scenario and identifying the primary trades is a study in itself.

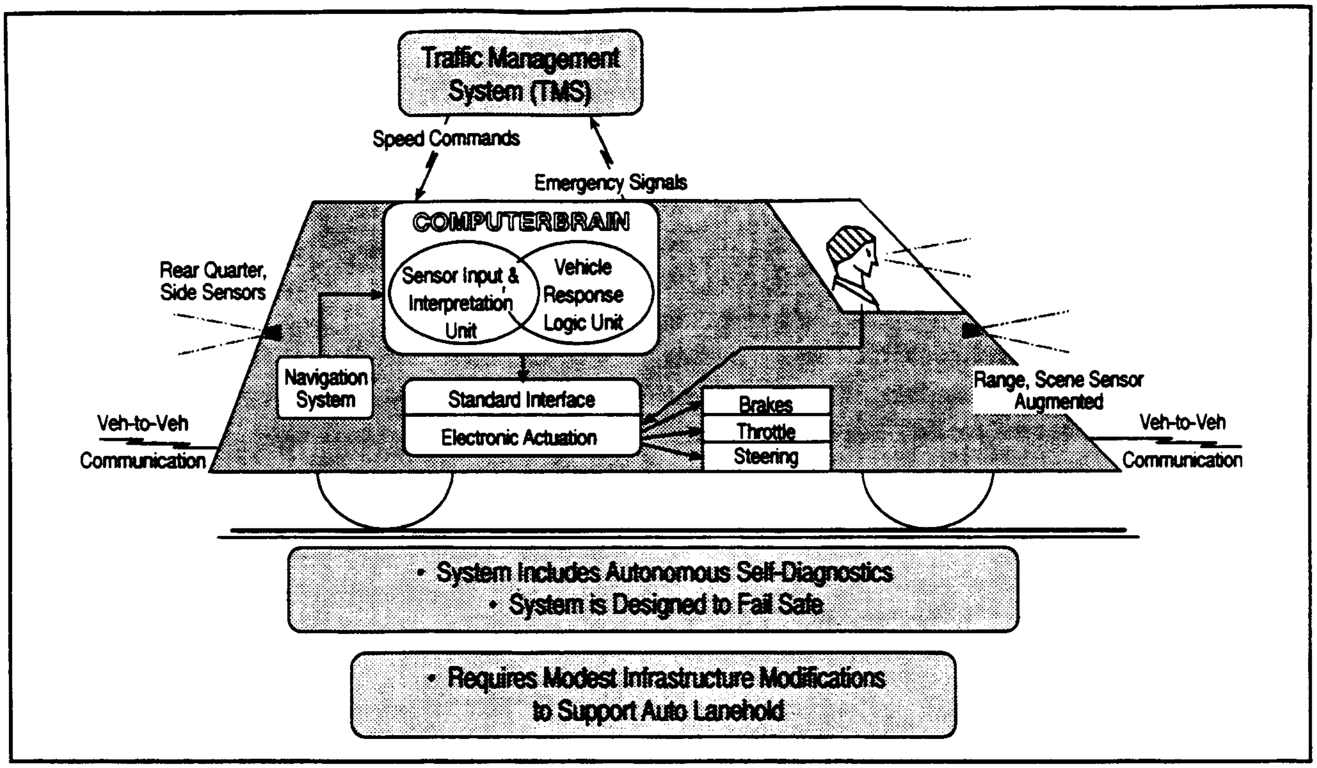

Figure 28. Add Automated Lane Change: Fully Automated Freeway Trip

SURFACE STREET OPERATION: THE INTEGRATED IVHS

In our opinion, this step will be as significant to the future of ground transport as the original introduction of automatic controls.

Freeways and highways basically constitute one long "link" on which the phenomenon of primary interest is the longitudinal spacing between vehicles. The important variable is the spacing between vehicles, a variable most easily measured and manipulated from on board the individual vehicle. This leads naturally to the essentially autonomous mechanizations described.

On surface streets, the primary interest shifts to the "nodes", the intersections. Links are short, and particularly in high density regions the behavior on the links is largely dictated by the conditions at the node. The node, not the link, is the dominate influence on surface street traffic behavior.

This shift from link-behavior-dominated phenomena to node-behavior-dominated phenomena leads to a different mechanization for an automated vehicle system. Now two functions are needed to effectively control flow at an intersection. First, we continue to need to insure safe separation between vehicles in a vehicle stream; we are already getting the necessary information from the vehicles' Automated Vehicle Control system, and it seems sensible to continue to carry out this safe-separation function with an on-board system.

The second function is the macrocontrol of the traffic streams through the intersection, in essence the allocation of time-slots to each of the desired travel directions to optimize total throughput and perhaps bias some flow directions to prevent jam densities in other parts of an area-wide system. The information to perform this function is beyond the reach of any individual vehicle, but is that already being collected and used this way by the Traffic Management System (at least, in advanced systems). It only makes sense to continue with this functional allocation, but rather than send traffic commands to a driver, we will send them to the now much more versatile "Computerbrain" on board the vehicle. The driver is no longer in the loop.

We have made a fundamental change in the AHS architecture from essentially autonomous vehicles behaving in a self-organizing system, to an integration of the Smart Street with the Smart Car. The Advanced Traffic Management System (ATMS) provides macro-commands, and the on-board Automated Vehicle System executes them and provides safe micro-control. Figure 29 illustrate the notion of this new integration.

Who navigates? There are three options. The first is an on-board navigation system that is heading the vehicle toward the destination selected by the "driver-passenger", but reacting to congestion information furnished by the ATMS in route selection.

The second option is guidance by an even-more-capable ATMS: the "driver-passenger" informs the system of his or her desired destination and the ATMS furnishes the necessary commands to the vehicle.

The third is the "driver", whose control inputs go to the wheels, but modulated and modified to prevent any unsafe actions. It is quite likely that the nature of the drivers controls in this mode of operation will have changed dramatically, since there is no need for anything more than 'turn-left-at-the-next-corner" type of inputs. Figure 30 reflects this very important step in the metamorphosis of the Automated Vehicle System.

This is all, of course, distant conjecture. But two points are clear. The first is that once we move to surface streets, we are on the path to the driverless vehicle, with all its implications.

The second is that AHS - or AVCS - cannot be ignored in the development of an IVHS architecture. While there was little interplay when the system was confined to the freeway, when the first steps toward total-trip-automation are taken, the AVCS system becomes inextricably intertwined with the other elements of IVHS. In fact, this will become the heart of IVHS.

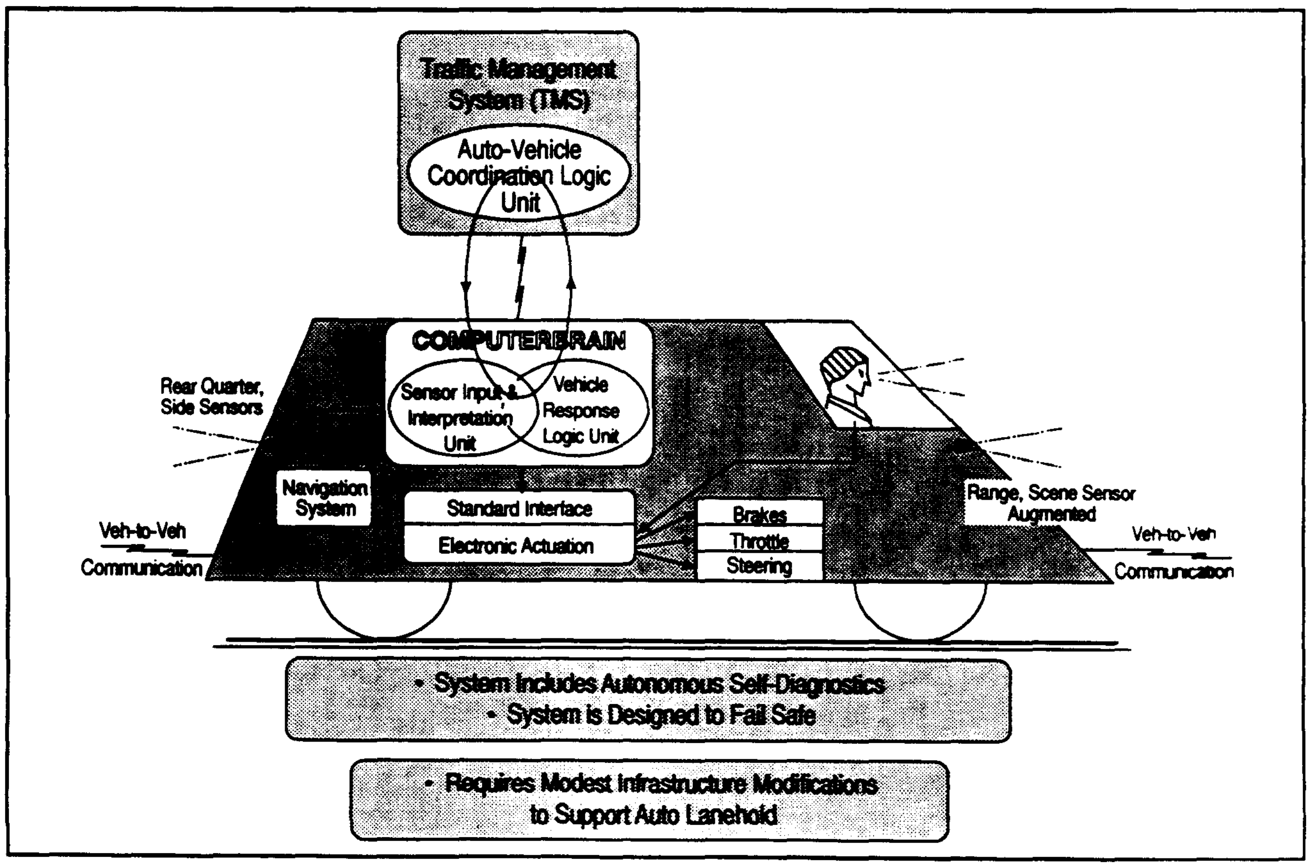

Figure 29. TMS-AVCS Integration
Fully Automated on Freeways and Traffic Controlled Surface Streets

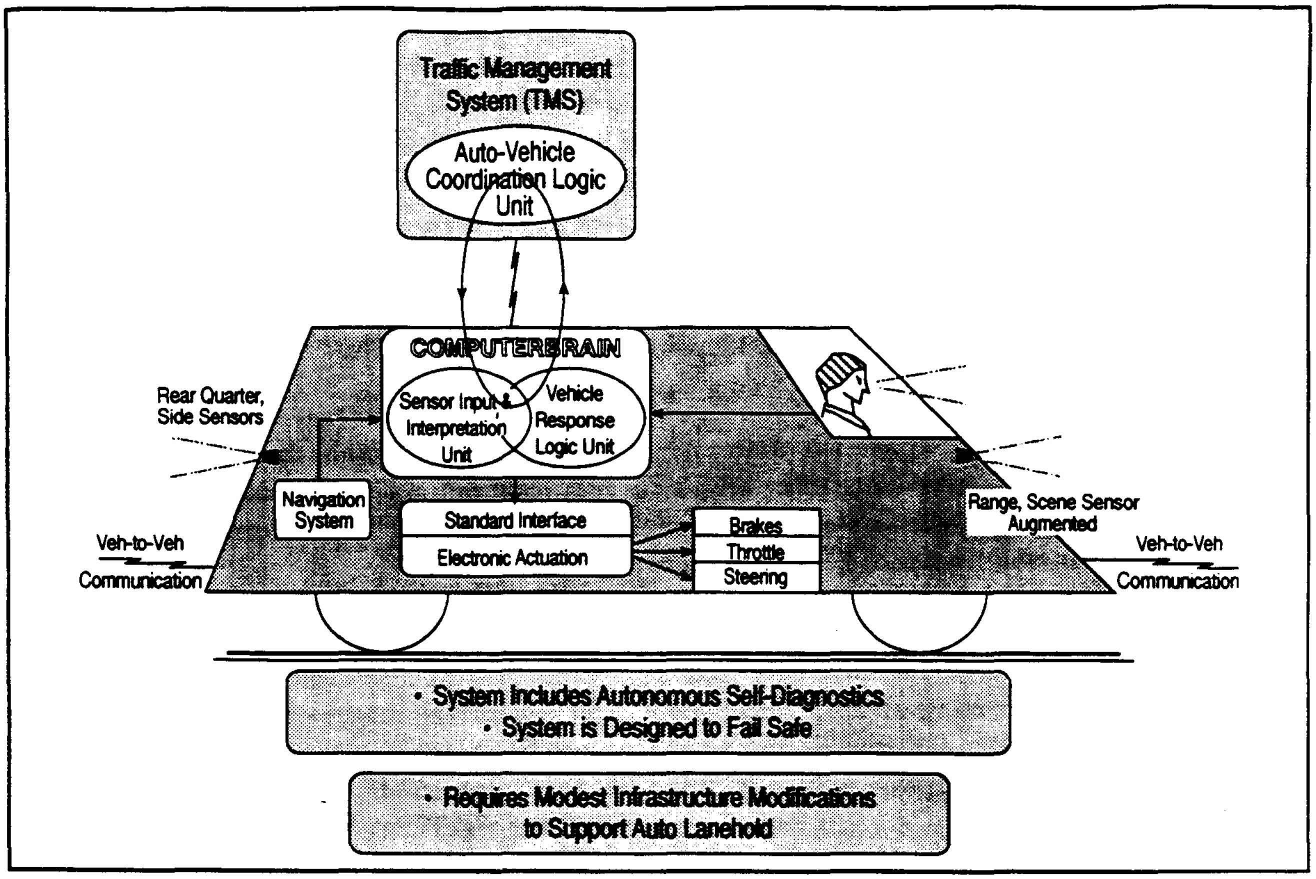

Figure 30. Automated Manual Control
The Safe Vehicle

POSTSCRIPT

There is an almost seamless path to a future for road transport that is almost beyond our imagination today. The technology is either in hand, or within stretching distance. The window of opportunity is open.

Appendix A

SPONTANEOUS PLATOONING: THE CALCULATION OF PROBABILITIES AND PARAMETERS

Vehicles can only platoon if both are equipped with the requisite systems. Since it will be many years before all vehicles are equipped, we will have equipped vehicles operating in mixed traffic with unequipped vehicles. It was, therefore, desired to calculate the probability of platoons of various sizes being able to form in such a mixed traffic environment.

Here we describe the calculations carried out to estimate this effect. The problem is complex and dynamic, and detailed simulation like carried out by Agre and Clare (Reference 3) is the preferred approach to analyzing the problem. Such simulation is well beyond the scope of this study.

We assume that equipped and unequipped vehicles are mixed at random. We also assume that there are always some vehicles preparing to exit the freeway at each ramp that, if they are part of a platoon, must break up or break of from that platoon.

The spread sheet used in the calculations is attached. We will comment on the points not considered self-explanatory.

CL is average vehicle length in feet.

DECELA is the maximum deceleration capability of the lead vehicle in g's, and DECELB is that of the following vehicle. Here we assumed it was 85 percent of that of the lead vehicle. The DELAY is the braking delay of the following vehicle. It was varied linearly with proportion of Autoplatoon-equipped vehicles, as shown in the sample spread sheet, also attached. These parameters were used to calculate SAFEGAP, the average spacing between vehicles. This average value was a surrogate for the mix of manual safegaps where the following vehicle was unequipped, and auto-safegaps where the following vehicle was equipped.

p is the probability that a vehicle is equipped with Autoplatoon, and q that it is not.

The next four variables, PSINGLE ... PQUAD, are the probability that a given vehicle will be part of a platoon of size n (i.e., SINGLE, DOUBLE, TRIPLE, QUAD). A "platoon" of size one is a single vehicle.

The variables PPLATn give the probability (the proportion) of platoons of size n.

DISTn (DIST1 through DIST4) give the total distance in the lane taken up by a platoon of size n. As can be seen, it assumes 3 feet between vehicles and SAFEGAP between platoons.

NVEHICLES calculates the vehicle density - the total number of vehicles in one mile.

The next four variables give the number of platoons of a given size. At this point they are artificial, calculated only out of curiosity, because they have no constraint on size from exitting vehicles that would prevent their build-up. Note that on the sample, when all vehicles are equipped, all the platoons are the maximum size. Without the constraint on platoon size built-in, there would be just one solid platoon of infinite size.

We now introduce constraints. With exitting vehicles there are a number of considerations. First, the proportion of vehicles that are exitting is given by the ramp spacing (RS) divided by the average trip length (TL). We ignore trying to treat trip length as a distribution.

Second, all the exitting vehicles are not Autoplatoon-equipped; only those that are equipped will affect the platoons. This is accounted for in the calculations.

Third, for 3 and 4-vehicle platoons, the probability that the exitting car comes from the outside vehicles in the platoon is, in general, different from the probability that it is an interior vehicle. This probability of an exterior vehicle is given by 2K/n, and that of an interior vehicle by 1-2K/n, where n is greater than 2. K is a factor to adjust for the impact of average trip length: if trips are long and vehicles have been entering regularly, the odds are high that the exitting vehicle - which has been in the lane for a long time - has become an interior vehicle, in which case K is nearly zero. If trip lengths are snort, then there is a much better chance that the exitting vehicle could be an outside vehicle, in which case k is close to one. We could only guess at the relationship, and we ultimately elected to leave K at 1 for the results shown.

The last consideration is the distribution of exitting vehicles among the platoons. The probabilities we have calculated tell us how many vehicles (probably) are leaving platoons of a given size, but they do not tell us the distribution among them. Largely to simplify the problem - which was already complex enough for this brief analysis - we assumed that each exitting vehicle cam from a different platoon. If the choice of values produced more exitting vehicles from platoons of size n than there were of size n, we zeroed out that size platoon.

This last assumption biases the results toward more smaller platoons and less larger ones, so will distort the distribution of platoon sizes. But as noted, it does not seem to materially affect the estimates of maximum flow potential, our key interest here.

Last, if the space required to support the entry and exit maneuvers is greater than normal safegaps, then some provision should be made for it. Prior analyses lead us to think that it is unlikely to be larger than 15 percent, and may be negligible. This is a problem in itself, since the net space required depends on the time the maneuvers take, the number of vehicles involved, and conditions in the next lane. We did not attempt to accommodate it here.

PLATOONING CALCULATIONS

MPH	60
CL	18
SAFEGAP	100
PERCENTEQUIP	0
RAMPSPACING	1
TRIPLENGTH	10
p	=0.01*PERCENTEQUIP*(1-(RAMPSPACING/TRIPLENGTH))
q	=1-p
PSINGLE	=q+p*q^2
PDOUBLE	=2*p^2*q^2
PTRIPLE	=3*p^3*q^2
PQUAD	=4*p^4*q^2
PFIVE	=5*p^5*q^2
PSIX	=6*p^6*q^2
PSEVEN	=7*p^7*q^2
P8	=8*p^8*q^2
P9	=9*p^9*q^2
P10	=10*p^10*q^2
P11	=11*p^11*q^2
P12	=12*p^12*q^2
CHECK: SUM=1?	=SUM(B9+B10+B11+B12+B13+B14+B15+B16+B17+B18+B19+B20)
DIST1	=CL+SAFEGAP
DIST2	=2*CL+3+SAFEGAP
DIST3	=3*CL+2*3+SAFEGAP
DIST4	=4*CL+3*3+SAFEGAP
DIST5	=5*CL+4*3+SAFEGAP
DIST6	=6*CL+5*3+SAFEGAP
DIST7	=7*CL+6*3+SAFEGAP
DIST8	=8*CL+7*3+SAFEGAP
DIST9	=9*CL+8*3+SAFEGAP
DIST10	=10*CL+9*3+SAFEGAP
DIST11	=11*CL+10*3+SAFEGAP
DIST12	=12*CL+11*3+SAFEGAP
NVEHICLES	=5280/(PSINGLE*DIST1+0.5*PDOUBLE*DIST2+0.333*PTRIPLE*DIST3+0.25*PQUAD*DIST4+0.2*PFIVE*DIST5+0.167*PSIX*DIST6+0.143*PSEVEN*DIST7+0.125*P8*DIST8+0.111*P9*DIST9+0.1*P10*DIST10+0.091*P11*DIST11+0.083*P12*DIST12)
NSINGLES	=PSINGLE*NVEHICLES
NDOUBLES	=0.5*PDOUBLE*NVEHICLES
NTRIPLES	=0.333*(PTRIPLE/PSINGLE)*NSINGLES
N4	=0.25*(PQUAD/PSINGLE)*NSINGLES
N5	=0.2*(PFIVE/PSINGLE)*NSINGLES
N6	=0.1667*(PSIX/PSINGLE)*NSINGLES
N7	=0.1429*(PSEVEN/PSINGLE)*NSINGLES
N8	=0.125*(P7/PSINGLE)*NSINGLES
N9	=0.1111*(P8/PSINGLE)*NSINGLES
N10	=0.1*(P9/PSINGLE)*NSINGLES
N11	=0.09091*(P10/PSINGLE)*NSINGLES
N12	=0.08333*(P11/PSINGLE)*NSINGLES
FLOW	=MPH*NVEHICLES