Intelligent Transportation: Serving the User Through Deployment

Proceedings of the 1995 Annual Meeting of ITS AMERICA

ITS America

Washington, D.C.
March 15–17, 1995

Volume 1

HIGHWAY AUTOMATION USING PLATOONS

Steven E. Shladover
University of California, Berkeley
Richmond, CA

ABSTRACT

This paper reviews the reasoning behind the concept of operating automated vehicles in closely spaced platoons as part of an automated highway system (AHS). The issues of highway capacity and safety are discussed, with particular reference to estimates of the achievable capacity and of the relationship between vehicle spacing and crash-impact speed. A brief history of automated platoon concepts is provided, along with answers to some of the questions most frequently raised by those who are skeptical of platoon operations. The main body of the paper reviews recent research findings about platooned AHS, and the paper concludes with identification of the remaining problems that need to be solved before platooned AHS can become operational.

INTRODUCTION

The advent of the federal AHS program, based on the guidance contained in the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA), has brought increased attention to the concept of highway automation. Within the past year, the AHS precursor systems analyses (PSA) projects and the proposals for the consortium that will conduct the systems definition phase of the program have provided opportunities for numerous people to think about AHS issues. Prior to these developments, AHS was generally regarded as something of a "fringe" issue in the world of intelligent transportation systems (ITS), and only received serious research attention within the Partners for Advanced Transit and Highways (PATH) program of the University of California, Berkeley.

Oohh! Aren't we full of ourselves! How about Navlab?

PATH researchers have been studying the design and operation of AHS in depth since 1988 and have already devoted about 150 labor years of effort to the subject. In the course of their study, they have devoted considerable attention to the issue of how to organize the movements of vehicles to maximize both capacity and safety. This has led to serious evaluations of the concept of grouped or platooned operations of vehicles and to full-scale testing and demonstration of such operations. In platooned operations, vehicles are clustered together in groups of up to 20 vehicles with very short spacings between vehicles within platoons and long spacings between platoons.

New arrivals to the study of AHS tend to regard platooned operations with considerable skepticism. The purpose of this paper is to explain the reasoning behind the concept of platooning and the knowledge gained over the past six years of intensive study. Hopefully, this discussion will dispel much of the misunderstanding of the concept that has been evident in recent commentaries on platooning and will address the concerns of skeptics. The paper concludes with identification of the remaining uncertainties about platooned AHS and issues that still need to be studied.

REASONS FOR OPERATING AUTOMATED VEHICLES IN PLATOONS

The platoon mode of operation was conceived as a way of expanding the envelope of capacity and safety that can be achieved by road vehicles. It is obvious that the one way of ensuring that there will be *no* vehicle crashes, injuries, or fatalities is to have no vehicles in motion. It is also readily apparent that as the speed and density of vehicles using the road system increase, the likelihood and severity of crashes will increase. The capabilities of drivers are the principal limitation here. Driver errors are responsible for well in excess of 90 percent of the crashes that occur today, and the limited ability of drivers to follow other vehicles produces the limitation on lane capacity. Drivers' limited ability to perceive changes in vehicle spacing, relative motion, and acceleration and their limited speed and precision of response ensure that lane capacity cannot generally exceed 2,200 vehicles per hour under manual control.

Electronic sensors, computers, and actuators can provide faster and more precise responses than human drivers. Moreover, these devices do not get drunk, fatigued, or emotionally upset and therefore perform very consistently compared with human drivers. These performance advantages should make it possible for electronically controlled vehicles to operate at significantly higher levels of capacity (shorter average spacings) and significantly higher levels of safety than today's manually driven vehicles. Drivers do not have accurate perceptions, however, of the safety of their vehicle-following distances and typically drive at closer spacings than they "should" if they are to avoid collisions when malfunctions occur. An automated system must be designed to be able to avoid virtually *all* crashes that could cause serious injuries or fatalities, which is a higher standard than drivers today apply to their own driving.

In order to be able to increase lane capacity, it is necessary to operate vehicles at closer *average* spacings (for the same speed). To do this, one must carefully consider the relationship between safety and the size of the gap or spacing. It is clear that if vehicles remain so far apart that they cannot ever collide upon occurrence of any single failure, there will be a substantial safety gain. If they remain that far apart, however, the capacity is likely to be reduced significantly below today's level. As the gap size is reduced, the opportunities increase for collisions to result from malfunctions.

The key issues in the attempt to improve both capacity and safety by use of automation are therefore centered around determination of: What conditions (gap sizes, environmental conditions, and vehicle malfunctions) can lead to crashes; how the severity of those crashes varies with the conditions; and what severity of crash could be considered acceptable. If one determines that *no* crash, however mild, is *ever* acceptable on an automated system, one must then abandon further consideration of AHS. This is because it is impossible to design and implement an absolutely perfect system that never suffers malfunctions. One can, however, certainly satisfy the requirement for no collisions in the absence of malfunctions.

Under the full range of possible vehicle operating conditions, there could, of course, be a wide variety of crash mechanisms, such as steering failures producing lane departure crashes, sudden accelerations of following vehicles, etc. For purposes of the capacity/safety analysis here, attention was confined to the rear-end crash caused by a malfunction that makes one vehicle (the "leading" vehicle) decelerate abruptly. Other crash mechanisms also need to be subjected to careful study.

If, for simplicity's sake, one considers only the operations of vehicles within a single lane, the factors that determine the impact speed of a rear-end crash are:

a. Initial spacing between vehicles

b. Deceleration rate of leading (malfunctioning) vehicle

c. Delay time from start of leading vehicle's deceleration to start of following vehicle's braking

d. Emergency braking deceleration rate of following vehicle

e. Speeds of both vehicles at time of malfunction.

Using data from the National Center for Statistics and Analysis of the National Highway Traffic Safety Administration (NHTSA), Hitchcock has shown how the severity of injury and probability of fatality to vehicle occupants are related to the impact speed (velocity difference between vehicles at time of impact).[1] This means that any system design should seek to minimize that impact speed. Hitchcock has also suggested, based on the NHTSA data, that an impact speed of 3.3 meters/second represents an approximate threshold between crashes that produce only mild-to-moderate injuries and those that may produce more severe injuries.[1] Of course, these effects are highly dependent on additional factors, such as the masses of the colliding vehicles, occupant restraints, and health and ages of the vehicle occupants.

There are three conditions under which a rear-end crash can occur, depending on the values of the parameters (a-e) defined above: (1) Follower hits leader before follower has started to apply brakes; (2) follower hits leader while both are braking; and (3) follower hits leader after leader has stopped.

Condition (1) typically occurs when the initial gap between the vehicles is very small, while condition (3) typically occurs when the initial gap is fairly large. The no-collision conditions occur when the initial gap is large enough that the follower can stop just short of touching the leader or when there is no gap at all, so that the vehicles decelerate in constant contact with each other. The collision impact speeds can become quite large at intermediate spacings.[2,3] The safety argument in favor of platoon operations is based on avoiding the intermediate spacings associated with the higher collision-impact speeds. These spacings are comparable to the spacings that are often advocated for use with autonomous vehicle-follower systems.

The relationship between the crash impact speed and initial vehicle spacing is highly dependent on the parameters (a-e) defined above, and variations in the values of those parameters can have dramatic effects on the shape and magnitude of the impact speed-versus spacing curve. The real debates about platooned operations need to be focused on defining reasonable ranges for these parameter values and defining the degree of aversion to crashes of different levels of severity.

Under virtually all conditions and parameter values initial gaps between vehicles of the order of one meter or less lead to crash-impact speeds that are quite modest (even under a "worst case" condition of a 1 g deceleratio of the leader, with no response by the follower, the impact speed would be 4.47 m/s, or 10 mph). As the gap increases, the impact speed increases up to some maximum, the value of which is extremely sensitive to the parameters (a-e), before decreasing again until it reaches zero at the point where the follower is able to stop before touching the leader. Depending on the parameter values chosen, this no-crash spacing could vary widely (anywhere from 10 to 100 meters). The extreme sensitivity of the impact-speed-versus-spacing relationship to the parameters (a-e), several of which are very difficult to select, makes the determination of nominal vehicle-following gaps challenging and controversial.

Until these vehicle-following gaps have been selected, it is impossible to define the capacity that an AHS can achieve. The inherent difficulty of selecting the gap size is the primary reason that AHS capacity estimates by different investigators have varied so widely and have been so difficult to compare with each other. Instead of re-deriving capacity estimates, one may simply refer to Shladover,[3] where capacity estimates were derived for several sets of parameter values representing both "optimistic" and "pessimistic" combinations of assumptions. These illustrate the wide variability in capacity estimates, the limited potential for capacity increases without using platoons (unless some very optimistic assumptions are made), and the phenomenon of diminishing returns with respect to platoon length as the platoons become longer. The guiding principles behind these derivations have been to assume as small a gap as possible within platoons (nominally 1 m) and to use conservative assumptions to select the gap between platoons in order to minimize the probability of any crash involving more than one platoon.

For example, in order for an automated system of single vehicles (without platoons) to reach a capacity of 2,700 vehicles per hour per lane at a 30 m/s cruise speed, it is necessary to assume that the failed leading vehicle decelerates at no more than 0.5 g and the follower can decelerate at least at 0.4 g within no more than 100 ms. Under this set of assumptions to govern *interplatoon* spacings, operations in five-vehicle platoons would provide almost 7,700 vehicles per hour, while 10-vehicle platoons would reach 10,000, and 20-vehicle platoons would push 11,800. On the other hand, if the failed leader decelerates at 2 g and the follower can only decelerate at 0.3 g within 300 ms, the single vehicle capacity is only 600 vehicles per hour, and even five-vehicle platoons can only bring it up to about 2,600 at 30 m/s. Platoons of 20 vehicles would be needed to get the capacity up to 6,700 vehicles per lane per hour under these conditions. The achievable capacities in the end are likely to be somewhere between these extremes, along the lines of the estimates shown in Figure 1.

HISTORY OF AUTOMATED PLATOON CONCEPTS

The idea of operating automated vehicles in platoons did not first arise as part of the discussion about the AHS program, but dates to the period of intense activity on automated guideway transit (AGT) systems in the 1970s. Shladover[4] includes a listing of 22 citations to published papers and reports about automated platoon concepts that

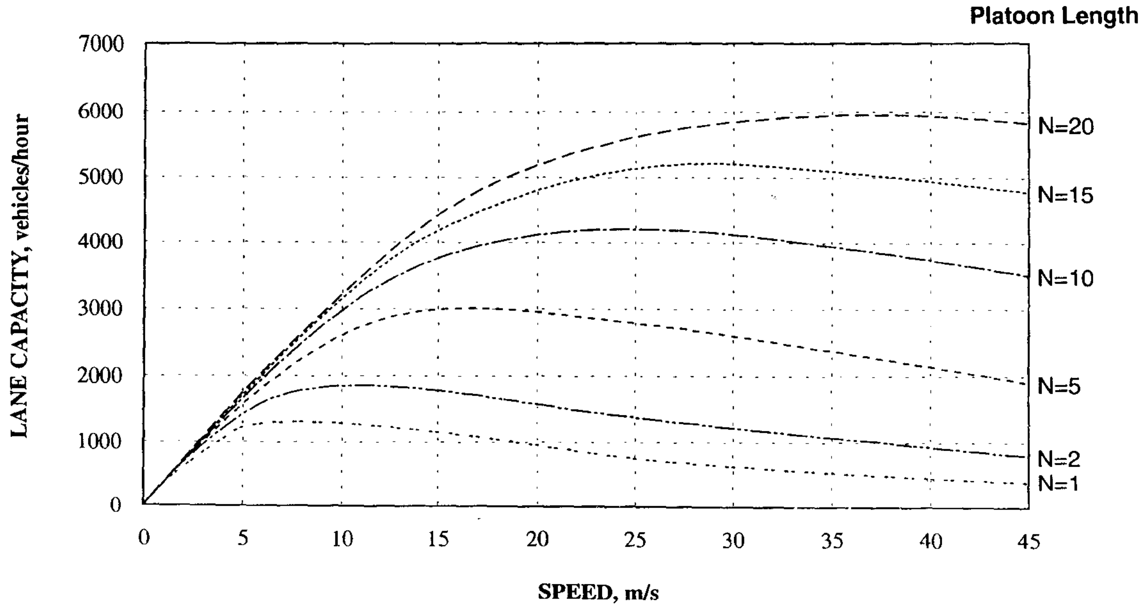

Figure 1. Lane capacity of a platoon system under intermediate assumptions (0.7 g failure, 0.3 g emergency braking, 0.2 s reaction delay)

were available as of 1978, not including his own. Much of this work was aimed at mechanical coupling of automated vehicles in dynamically reconfigurable "trains" rather than in platoons that would only be coupled by the action of their control systems. However, control-coupled platoons were considered by researchers from such organizations as General Motors[5] and Engins MATRA.[6,7] The MATRA experience is particularly interesting because researchers built a test track and a group of test vehicles that they operated under automated platooning in 1972-73 and, in a later reincarnation, in 1986-87. This project, called ARAMIS, involved platoons of up to 25 small transit vehicles operating at speeds of up to 80 kilometers/hour and 30-centimeter spacings and using both ultrasonic and optical ranging sensors. Existing papers in the open literature describing the first generation of this system[6,7] do not give many details about technological implementation, but nevertheless provide informative reading.

Shladover[4] describes the findings of a comprehensive analysis of the use of automated platoons or mechanically coupled trains of small transit vehicles to provide personalized rapid transit service on special guideways. This report and a series of technical papers based on its findings[2,8-10] define the capacity and safety issues, the nonlinear longitudinal-control-system design considerations, and the implications of merging streams of platooned traffic. This work did not, however, extend beyond analysis into experimental verification.

More recently, in association with the PROMETHEUS program, Volkswagen developed an automated platoon system called "convoy driving." Because of proprietary information restrictions, there has been virtually no public documentation of the technical characteristics of this system, although there is a very impressive videotape of a 1989 demonstration of the system on a test track. This shows operation of multiple-vehicle platoons at highway speeds under fully automatic steering and longitudinal control, and with spacings that appear to be one meter or less. The video includes a demonstration of emergency braking on wet pavement and a segment in which the driver of the test van turns on the automatic control system and then leaves the driver's seat to take up a position in the passenger's seat, showing his confidence in the system's ability to drive the vehicle without his intervention. The Volkswagen effort was terminated after the initial demonstration, apparently because German public officials were very sensitive to Green Party opposition to a system that was perceived as too "pro-automobile."

In 1988, researchers in the California PATH Program picked up from where Shladover[4] left off and began more in-depth investigations into the control design and system operational implications of automated platooning for AHS. The principal findings of this research will be covered in a later section of this paper.

MISCONCEPTIONS ABOUT AUTOMATED PLATOONING

Much of what has been said and written about automated platooning in recent years has been based on several misconceptions about the concept. When these misconceptions are resolved, it becomes apparent that the problems with platooned operations are not nearly as serious as they might appear at first glance.

Platooning Is Very Complicated and Expensive

The large majority of the hardware and software needed to make platooned AHS work are also needed for fully automated but nonplatooned AHS. It is important to concentrate on those items that would need to be *different* in order to make platoons work. The only features that would be peculiar to a platooned AHS are: (1) Vehicle-vehicle communication systems capable of transferring reasonably high-bandwidth control information (kilobytes per second, not megabytes per second); (2) ranging sensors with accuracy of several centimeters within an overall range of a few meters; and (3) software logic for joining and splitting platoons.

Sensor Requirements for Platooning Are Very Demanding

Ranging sensors for the very short-range application of measuring the spacings between vehicles within a platoon appear to be easier to develop than the ranging sensors that would be needed for larger-gap AHS operations and much easier to develop than those that would be needed for adaptive cruise control or collision avoidance applications. The short-range sensors have a very large "target" to see in front of them and do not need to employ much sophistication to identify that target from among many others within the field of view.

Within the past year, PATH researchers have tested ultrasonic, FMCW radar, and infrared triangulation sensors for vehicle-to-vehicle ranging at a variety of spacings. The ultrasonic system gives extremely good ranging information at gaps of 7 m or less except in dusty conditions, while the IR triangulation system is effective up to about 20 m range under static conditions, and the radar works very well between 1.5 and 10 m under dynamic conditions. There are no fundamental reasons why these technologies should not be effective at vehicle-to-vehicle gaps on the order of 1 m (which could correspond to somewhat larger sensed gaps, depending on where the sensors are mounted on the vehicles). The measure-ments from one or more of these types of sensors can be combined with measurements of vehicle location relative to permanent markers installed in the pavement (which would serve primarily as lateral guidance references) using data-fusion software to produce extremely robust estimates of vehicle spacings.

Platooned Operations Would Expose Travelers to Frequent Crashes

The platoon operating concept is firmly based on the principle that there shall be no crashes in the absence of malfunctions. There is no intention to have platooned vehicles acting like amusement park "bumper cars." The nominal spacing between vehicles within a platoon must be large enough that it can accommodate normal variability in the response of the vehicles within the platoon based on differences in external force loadings, vehicle condition, and control-system inaccuracies. One of the primary goals in the design of the control systems is to minimize the variability in spacing so that the nominal gap can indeed be made small while still avoiding inadvertent contact between vehicles.

Crashes of platooned vehicles should be almost as rare as crashes in non-platooned automated vehicles, but when they occur they should be much less severe. Crashes could only occur as a result of a malfunction, not as a part of normal operations. While malfunctions are intended to be rare, particularly with the added protection provided by automated check-in functions, they cannot be eliminated entirely. When they do occur, the response of the overall system must be designed to be safe. Among other things, the nominal intraplatoon spacing must be large enough that the occurrence of a "typical" malfunction cannot ensure the occurrence of a crash. In other words, the gap between vehicles within a platoon must be large enough that each follower has the opportunity to reach its full braking rate between the time the leader suffers its malfunction and the time the follower would collide with it. This means that crashes within a platoon should only occur when there are multiple malfunctions or particularly severe malfunctions (ones in which the leader decelerates more rapidly than the follower's maximum braking capability).

Table 1 provides some sample numbers to illustrate the significance of this for intraplatoon gaps. The mild failure (coast down after propulsion system failure) is assumed to produce a deceleration rate of 0.1 g, while the severe failure (multiple tire blow-out) would cause the leader to decelerate at 0.5 g. Using today's automatic braking technology, it would probably take about 250 ms for an automatic braking system to reach full braking effectiveness. This is expected to be reduced to 100 ms in the next few years, based on ongoing laboratory developments. The "manual control" columns in Table 1 assume a highly skilled and alert driver rather than a typical driver. For a typical driver, increasing the sense-and-initiate time from 500 ms to 1,500 ms for the severe failure would increase the minimum spacing from the 2.5 m value shown in the table to 10 m. This kind of difference is consistent with the differences between the spacings seen in normal freeway driving and the spacings seen on race tracks.

Failure Severity	Manual Control (Typical Driver)	Manual Control (Highly Skilled)		Automatic-Autonomous (10 cm sensor resolution)				Automatic-Cooperative			
		Severe	Mild	Severe		Mild		Severe		Mild	
Braking Lag Time (ms)											
Sense problem/initiate action											
Severe failure (0.5g)	1500	500		200	200			40	40		
Mild failure		—	1500			450	450			40	40
Communicate			—	—	—	—	—	20	20	20	20
Apply brake pressure											
Normal system	500	500	500	250	—	250	—	250	—	250	—
Advanced system		—	—	—	100	—	100	—	100	—	100
Total Times (ms)											
Normal braking	2000	1000	2000	450	—	700	—	310	—	310	—
Advanced braking		—	—	—	300	—	550	—	160	—	160
Minimum Spacings (m) to Avoid Crash											
Normal braking	10.00	2.50	2.00	0.506	—	0.245	—	0.240	—	0.048	—
Advanced braking		—	—	—	0.225	—	0.151	—	0.065	—	0.013

Table 1. Braking lag times (milliseconds) and minimum spacings (meters) to avoid crashes when failures occur

As Table 1 shows, automated systems need spacings of no more than 0.5 m to ensure that the follower is able to initiate braking before touching the failed leader. The spacings for the cooperative system are substantially shorter than for the autonomous system because the failure of the leader can be communicated directly to the follower rather than having to wait for a change in the spacing to become noticeable to the follower's sensor system. The platoon concept is intended to be inherently cooperative in order to ensure stability of dynamic response. Thus, the worst case on this table that is applicable to platoons is 0.24 m, which assumes current braking capabilities.

Small-Gap Operations Within Platoons Will Be Alarming

This contention, although it is taken as an article of faith by some platoon opponents, cannot be proven or disproven until realistic human factors experiments are conducted on real vehicles. Some preliminary indications should become evident via driving simulator experiments. Together, these experiments can also be used to help design vehicle maneuvers so that gap-versus-time profiles can be specified in ways that are comfortable and reassuring. They can also provide useful guidance regarding the types of system status indicators that people prefer to have in order to provide assurance that the control system is functioning properly throughout its maneuvers.

PATH researchers have recently offered demonstration rides for visitors in a platoon of four vehicles operating at gaps of 4 m at speeds between about 12 and 30 m/s (see Figure 2). Although this size gap would be considered as serious tailgating in normal driving, it was not disquieting to the passengers of the test cars because the gap was maintained very precisely, and some of them even commented on how unexceptional the experience was. When the control system provides such tight control of gap, it gives the sensation that the vehicles are rigidly linked and the vehicle in front appears to be "pulling" the following vehicle along behind it.

RECENT RESEARCH ACCOMPLISHMENTS ON PLATOON OPERATIONS

The PATH research on platoon operations has already considerably expanded knowledge about how platoons could be made to work and how the platoon mode of operation would compare with individual vehicle operations (sometimes referred to as "free agents"). Some of the key findings are in the following areas:

Control Accuracy and Ride Quality

There is a fundamental trade-off between the accuracy of control response and the smoothness of ride that can be achieved. Control analyses and simulations under

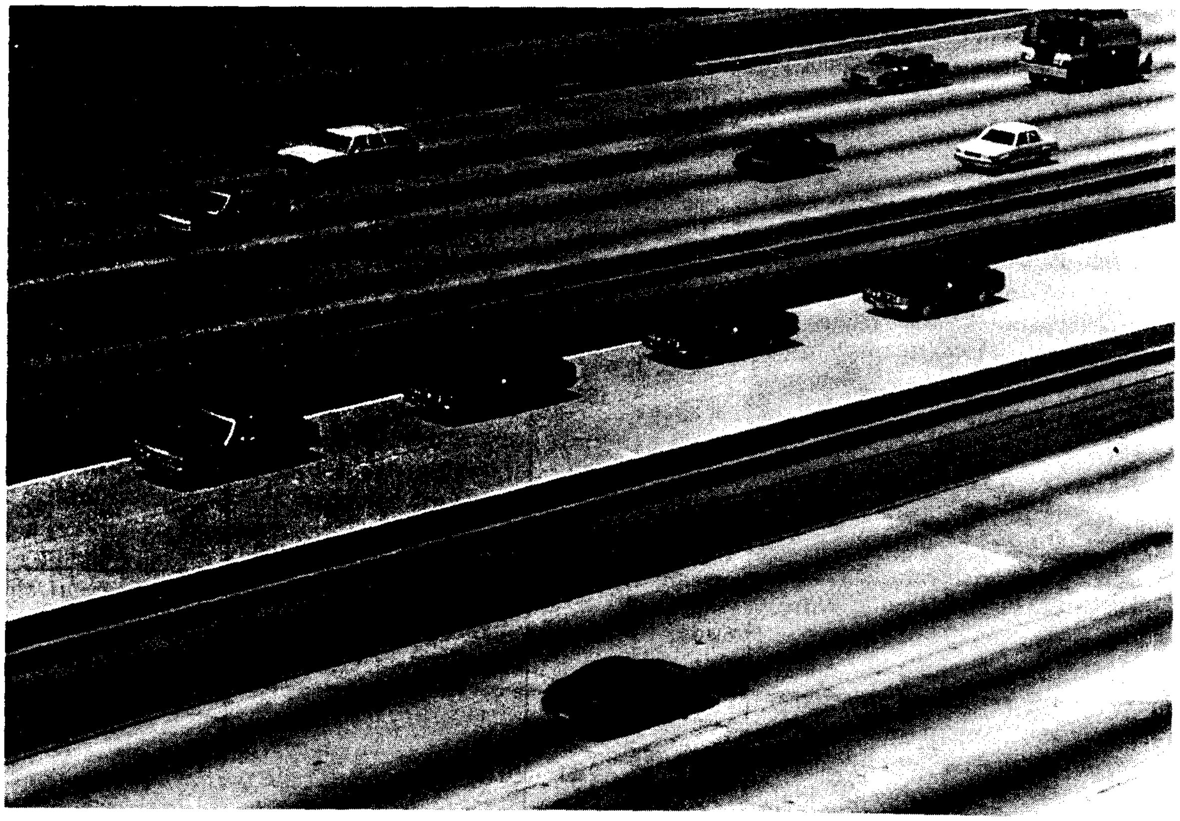

Figure 2. A platoon of four vehicles operating under automatic longitudinal control at gaps of 4 meters

...ed conditions have indicated that it should be ...le to achieve both high accuracy and high comfort. ...ecently, however, it has not been possible to verify ...testing of full-scale vehicles. Experiments ...cted in the summer of 1994 using a platoon of four ...icles have finally shown that a very smooth ride ...turbances small enough to be imperceptible to riders) ...be achieved while maintaining spacing to within 30 ...of the desired value under steady driving conditions ...d within 50 cm under a wider range of conditions, ...luding during acceleration and deceleration maneuvers ...ducted on both positive and negative slopes of up to 3 ...rcent.[11] These experiments have also shown that ...sturbances can be sufficiently attenuated that the ride in ...e fourth vehicle is not perceptibly different from the ride ...the second vehicle.

Actuator Performance Requirements

The key actuators for longitudinal control within a platoon have to do with the throttle and brake. It was demonstrated in 1992 that good engine control could be achieved with a throttle actuator having a response rate of at least 500 degrees per second.[12] Braking requirements are somewhat more difficult to achieve because of inherent lags built into existing power-braking-assist systems. A brake actuation system that acts through the brake booster (by acting on the brake pedal, for example) does not appear to be adequate for platoon use because it has excessive lag time. New designs that act directly at the master cylinder or the individual calipers at the wheels are expected to have fast enough response to meet ride quality needs for use in closed-loop platoon-control systems, but this cannot be proven until the newer hardware is tested on vehicles during 1995.

Sensor and Communication System Performance Requirements

A combination of analyses, design studies, laboratory tests, and experiments on full-scale vehicles has enabled some preliminary evaluations of the performance that should be needed from ranging sensor and vehicle-vehicle communication systems in order to support platooned operations. Significantly, these appear to be achievable using technical approaches that should not be inherently costly or exotic.

The ranging-sensor requirements that are peculiar to platooning are the need to operate down to a very short range (potentially, though not necessarily, as short as 1 m) and to provide range measurements to reasonably high precision at these short distances. In order to provide smooth control response, the range (and range rate) measurements need to be relatively stable and have low noise content. The control system's signal-processing software needs to be able to filter out anomalous individual data points, but systematic measurement errors are more difficult to eliminate. The range measurements should be accurate to within 5 to 10 cm of the true range at the closest spacings in order to permit the control system to work well. This appears to be readily achievable using several of the sensors with which PATH researchers have experimented.

The vehicle-vehicle communication system must be able to supply information about the speed and acceleration of the platoon leader and each leading vehicle to each following vehicle, and must be able to serve as the conduit for emergency status information. The cycle time for each exchange of information should be in the range of 20-50 ms to promote good platoon dynamic response. Given the amount of information that must be provided and the need for error detection and correction, as well as provisions for multiple transmissions to reduce the effective communication-error rate, the intraplatoon communication system appears to need a capacity in the range of 1060-1820 bits/second for each vehicle.[13] This appears to be achievable by such means as optical wireless (infrared) and microwave mobile radio.

Platoon Collision Dynamics

The common calculations used to study the potential for collisions among vehicles within a platoon are based on simple kinematic analyses. These are not adequate for addressing the complications that arise with multiple-vehicle collisions, diverse vehicle masses, alternative emergency-response strategies, and the impact-absorbing effects of bumper systems. These issues have been addressed in a recent PATH study led by Professor Benson Tongue of UC Berkeley.[14]

The dynamics of multiple-vehicle collisions can be quite complex, and often the most severe crash does not occur between the first two vehicles to contact each other. Mass differences among the involved vehicles can produce further "strange" effects. In all cases, though, availability of information about the platoon leader (or the first vehicle involved in the crash) has been shown to improve the ability of the control system to avoid any crashes (or reduce the number of vehicles involved). Providing information to each vehicle about the movements of the vehicles *behind* it also makes it easier to avoid or mitigate crashes. It is difficult to draw simple conclusions from this study because of the complicated interactions among all of the variables that affect collision dynamics. Further research is continuing in this area in order to lead to the development of robust strategies for handling intraplatoon collisions.

Probabilities of Injury and Fatality

Vehicle crashes are rare events, produced by combinations of random phenomena that cannot be represented purely deterministically. For any given type of crash, the severity of an individual occurrence (probability of causing serious injuries or fatalities) is influenced by the following random variables:

a. Deceleration rate of failed vehicle, given the type of failure that occurred and the condition of the vehicle's tires and the road surface

b. Braking rate of following vehicle, given its loaded mass, the condition of its brakes and tires, and the condition of the road surface

c. Delay time between failure and following vehicle's response

d. Speed and acceleration of each vehicle at the time of the failure

e. Masses and structural properties of both vehicles

f. Existence and use of occupant restraints in each vehicle

g. Ages and health of occupants of each vehicle.

Some of these factors (f,g), are obviously so random that they cannot be accommodated realistically in an analysis, while others (c,d) can be addressed directly in the AHS design. A recent PATH study by Hitchcock[1] has explicitly considered probability distributions of factors (a,b,e) in a series of Monte Carlo simulations to estimate the collision-impact speeds that would occur under both wet and dry road conditions. By use of data from the Crashworthiness Data System (CDS), the correlation between collision-impact speed and injury level was estimated. Combining this with the Monte Carlo simulation results led to a first set of estimates of the probabilities of serious injuries and fatalities under different failure conditions involving platoons as well as vehicles operating under autonomous adaptive cruise control (AACC) and point-follower control systems.

This study showed that the rates of serious injuries and fatalities were lowest for the closely spaced platoon system under almost all conditions, largely because the crashes that did occur within the platoons were at impact speeds lower than those needed to cause serious injuries or fatalities. By contrast, the AACC systems appeared to be vulnerable to much more serious collisions, particularly if operated at high densities. This means that they must have significantly higher reliability against failures that cause abrupt decelerations than the platooned AHS if their overall injury and fatality rates are to be comparable. The results of this study imply that the mean time between abrupt-deceleration failures for a platooned AHS vehicle would need to be on the order of 10^4 hours in order for the injury rate for that type of accident to be about 10 percent of today's freeway driving injury rate.

Aerodynamic Drag Reductions

Recent PATH wind-tunnel experiments conducted by Professor Browand and colleagues at USC have indicated the potential for reducing aerodynamic drag by operating AHS vehicles in close-formation platoons.[15] This research has shown the relationship between drag force and vehicle spacing under various conditions, including crosswinds, for scale models of GM Lumina APV vehicles. The results indicate the potential for dramatic drag reductions, which improve as vehicle spacings become shorter. The closest spacings reported thus far are one-half vehicle length (approximately 2.5 m for these vehicles). Even at these spacings, the drag reduction approaches 50 percent for a long platoon, compared with the drag on an individual vehicle. Interestingly enough, all vehicles in the platoon show reduced drag, although the effect is stronger for the middle vehicles than it is for the first and last vehicles. The implications of drag reductions of up to 50 percent for fuel economy and pollutant emissions are extremely significant and need further exploration.

Energy Consumption and Emission Effects

The aforementioned reductions in drag have been used as inputs to two studies that are considering the environmental implications of ITS. In one of these PATH projects, Dr. Barth of U.C., Riverside, is using mathematical models to predict changes in energy consumption and vehicle pollutant emissions that would result from a variety of ITS operations. His initial study of the platooned AHS has indicated that the drag reduction associated with short-headway platooning should reduce by about 25 percent the fuel consumption and pollutant emis-sions per vehicle as compared with an AHS using vehicles operating independently (as "free agents").[16] The reductions should be more substantial when compared with conventional manually driven traffic, with its stop-and-go cycles. The second study, by Browand's group, has estimated comparable fuel savings for large platoons operating at short spacings.[17]

These environmental benefits are extremely significant when compared with any of the proposed pollution-control measures, except for radical alternative propulsion systems and the most draconian demand-reduction regulations.

TECHNOLOGICAL CAPABILITIES NEEDED TO MAKE PLATOONING WORK

The ongoing PATH research on platooned AHS has helped to "demystify" the technology that will be needed to make platoons work. There are no dramatic breakthroughs needed in fundamental physics or engineering science, but there will need to be much careful engineering, safety-verified control software, refinement of technologies, and work on cost reductions. In this regard, platooned AHS is no different from any other kind of AHS.

The areas in which platooning imposes more severe performance requirements than other forms of AHS are: (1) Accurate short-range sensing; (2) fast, reliable vehicle-vehicle communication; (3) safety-verified cooperative maneuvering protocols; (4) an informative user interface to provide the driver with reassurance about the status of system performance and maneuvers; (5) very fast and precise throttle- and brake-control actuators.

Specifics of several of these have already been addressed as part of the PATH research program and were discussed in a previous section of this paper.

REMAINING PROBLEM AREAS

The foregoing is not intended to convey the idea that all problems related to platooned operation of AHS have been solved and the country is ready to deploy a system tomorrow. There are several open issues that have not yet been fully addressed and that could represent problems peculiar to platooning (rather than to AHS in general). These are as follows:

Human Factors and User Acceptance

Acceptability of platooned AHS to a representative sampling of drivers cannot be proven until a highly refined prototype is available for human-factors experimentation. Some preliminary indications should be given by the results of the ongoing Federal Highway Administration (FHWA)/Honeywell project on Human Factors Design of AHS, but these must remain preliminary because the experiments will be performed in a driving simulator rather than in a real vehicle.

Achievable Intraplatoon Spacing

Considerable research will still be needed to determine how small a spacing can be achieved between consecutive vehicles within an automated platoon. The answer must depend on the precision of the sensors, actuators, and control system, the robustness of the systems with respect to external disturbances, and the acceptability to users. Technological issues will require experimentation on test tracks under diverse conditions, while user acceptability will have to be determined as part of human-factors experiments.

Intraplatoon Collision Effects

The possibility of having collisions among the members of a platoon following a malfunction raises a number of difficult issues that still need to be resolved. These include the need to develop credible estimates of the probabilities of impacts of different severities and the need to define an acceptable threshold for each of these probabilities of occurrence. A combination of difficult technical and policy issues must be addressed in order to solve these problems.

Unusual Aerodynamic Effects

Although the general steady-state effects of platooned operations on vehicle aerodynamics have already been evaluated, there are some more subtle effects that are not yet fully understood. These include: (1) The transient aerodynamic forces that will occur in transient maneuvers when vehicles enter and leave platoons, and (2) the potential that very close vehicle-following may lead to a loss of cooling air flow to vehicle radiators or the ingestion of exhaust fumes from the leading vehicle into the passenger compartment of the following vehicle. These need to be studied through a combination of planned scale-model and full-scale testing.

CONCLUSION

Although various uncertainties remain about platooned operation of AHS, much has been learned in recent years. Results of this research certainly indicate that there is substantial promise to the concept and that it is worth continuing with research that addresses the remaining uncertainties. Platooned operation appears to offer some significant advantages relative to other implementations of AHS, and therefore it needs to remain under serious consideration for AHS research, development, and demonstration activities.

ACKNOWLEDGMENTS

This work was performed as part of the California PATH Program of the University of California. It was accomplished in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration. The contents of this paper reflect the

views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. A. Hitchcock, "Intelligent Vehicle-Highway System Safety: Multiple Collisions in Automated Highway Systems," PATH Research Report PRR95-10, Institute of Transportation Studies, University of California, Berkeley, February 1994.

2. S.E. Shladover, "Dynamic Entrainment of Automated Guideway Transit Vehicles," *High Speed Ground Transportation Journal* Vol. 12, No. 3 (Fall 1978): 87-113.

3. S.E. Shladover, "Potential Freeway Capacity Effects of Automatic Vehicle Control Systems," *Applications of Advanced Technologies in Transportation Engineering*, ASCE Conference, Minneapolis, MN, August 1991, pp. 213-217.

4. S.E. Shladover, "Operation of Automated Guideway Transit Vehicles in Dynamically Reconfigured Trains and Platoons," Reports UMTA-MA-06-0085-1 through -3, PB 300513, PB80-142862 and PB 80-198856, April 1979.

5. N.H. Triner and L. Robertson, "Guideway Design Considerations for the General Motors Dual Mode Transit System," paper presented at First International Conference on Dual Mode Transportation, Transportation Research Board, Washington, DC, June 1974.

6. J.P. Maury, "The ARAMIS PRT System," SAE Paper 740143, 1974.

7. J.P. Couplan, "Le Système de Transport Urbain ARAMIS," *Proceedings of First International Conference on Transportation Research*, Bruges, Belgium, 1973 (Transportation Research Forum), pp. 351-354.

8. S.E. Shladover, "Longitudinal Control of Automated Guideway Transit Vehicles Within Platoons," *Journal of Dynamic Systems, Measurement and Control* Vol. 100, No. 4 (December 1978): 302-310. (Also ASME Paper No. 78-WA/DSC 13.)

9. S.E. Shladover, "Vehicle-Follower Control for Dynamic Entrainment of Automated Guideway Transit Vehicles," *Journal of Dynamic Systems, Measurement and Control* Vol. 101, No. 4 (December 1979): 314-320. (Also presented at Joint Automatic Control Conference, Denver, Colorado, 1979.)

10. S.E. Shladover, "Operation of Merge Junctions in a Dynamically Entrained Automated Guideway Transit System," *Transportation Research* Vol. 14A, No. 2 (April 1980): 85-112.

11. S.B. Choi and J.K. Hedrick, "Vehicle Longitudinal Control Using an Adaptive Observer for Automated Highway Systems," submitted to *IEEE Journal of Circuits, Systems and Computers* (special issue on automotive electronics).

12. K.S. Chang, J.K. Hedrick, W.B. Zhang, P. Varaiya, M. Tomizuka, and S.E. Shladover, "Automated Highway System Experiments in the PATH Program," *IVHS Journal* Vol. 1, No. 1 (Spring 1993).

13. S.R. Sachs and P. Varaiya, "A Communication System for the Control of Automated Vehicles," Technical Memorandum 93-5, PATH, Institute of Transportation Studies, University of California, Berkeley, September 1993.

14. Y.T. Yang and B.H. Tongue, "Intraplatoon Collision Behavior During Emergency Operations," *Vehicle System Dynamics* Vol. 23, No. 4 (May 1994): 279-292.

15. M. Zabat, S. Frascaroli, and F.K. Browand, "Drag Measurements on 2, 3, and 4 Car Platoons," SAE Paper No. 940421, International Congress & Exposition, Detroit, MI, 1994.

16. M.J. Barth, "Evaluating the Impact of IVHS Technologies on Vehicle Emissions Using a Modal Emissions Model," National Conference on Intelligent Transportation Systems and the Environment, Arlington, VA, June 1994.

17. M.S. Zabat, N.S. Stabile, and F.K. Browand, "Estimates of Fuel Savings From Platooning," submitted for presentation at ITS America Fifth Annual Meeting, Washington, DC, March 1995.